

## **PUBLIC COMMENT**

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**in Response to the Environmental Protection Agency's  
Advanced Notice of Proposed Rulemaking on  
Regulating Greenhouse Gas Emissions Under the Clean Air Act,  
Docket ID No. EPA-HQ-OAR-2008-0318**

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## EXECUTIVE SUMMARY

In the Advanced Notice of Proposed Rulemaking (ANPR), published on 30 July 2008, the Environmental Protection Agency (EPA) solicited comment on analyses and policy alternatives regarding greenhouse gas (GHG) effects and regulation under the Clean Air Act (CAA). In particular, the EPA Administrator invited comment on "all issues relevant to making an endangerment finding, including the scientific basis supporting a finding that there is or is not endangerment under the CAA, as well as the potential scope of the finding (i.e., public health, welfare, or both)."

For several *decades* now, personnel in our organization have been working and publishing on matters related to earth's rising atmospheric carbon dioxide (CO<sub>2</sub>) concentration as they pertain to both the climate and biology of our planet. During the course of that endeavor, we have examined literally *thousands* of peer-reviewed scientific journal articles, the results of which examination have led us to conclude that increasing atmospheric CO<sub>2</sub> concentrations will exert a relatively benign influence on earth's climate, while simultaneously providing manifold benefits to humanity and nature alike.

Support for this thesis has been presented by us via the publication of *CO<sub>2</sub> Science*, an online journal created in 1998 by the non-profit Center for the Study of Carbon Dioxide and Global Change ([www.co2science.org](http://www.co2science.org)), where we have published editorials on topics of current concern and mini-reviews of recently published peer-reviewed scientific journal articles, books, and other educational materials. During that time we have amassed an incredible amount of material, arguably the largest database of its kind on the Internet, all of which material has been archived in a massive *Subject Index* that presently contains hundreds of topics and sub-topics relevant to the global warming debate.

Although it is impossible for us to reproduce the volume of information contained in our website that supports our thesis here, we have elected to present a subset of the topics and issues we feel will be most helpful to the EPA Administrator in making a ruling on the Endangerment Issue. Many of the studies we cite are not referenced in the Endangerment Technical Support Document (TSD) to the ANPR, which makes it particularly important for the Administrator to review this material in order to ensure, as stated in the ANPR, that the "totality of the observed and projected effects that result from current and projected [greenhouse gas] concentrations" have indeed been investigated.

To assist the EPA in its evaluation of such materials, we have included hyperlinks throughout this document by which the Administrator may locate additional information on a given topic, as posted on our website, via the simple act of clicking a computer mouse. We begin by presenting a list of key findings as contained in the TSD's Executive Summary (**bolded typeface for ease of identification**), followed by our bulleted response to those findings, which are then fully addressed in the chapters of our submitted report below.

### Comments on the Key Findings in the TSD Executive Summary

The global average net effect of the increase in atmospheric GHG concentrations, plus other human activities (e.g., land use change and aerosol emissions), on the global energy balance since 1750 has been one of warming.

The majority of future reference-case scenarios (assuming no explicit GHG mitigation actions beyond those already enacted) project an increase of global GHG emissions over the century, with climbing GHG concentrations and rising net positive radiative forcing.

Through about 2030, the global warming rate is affected little by different scenario assumptions or different model sensitivities.

All of the U.S. is very likely to warm during this century, and most areas of the U.S. are expected to warm by more than the global average.

- Today's state-of-the-art climate models suffer from a number of major inadequacies stemming from both the treatment and *non*-treatment of pertinent phenomena, some of which deficiencies could alter even the *direction* of projected climate change.
- The set of problems that currently restricts our ability to properly model a whole suite of cloud-related processes likewise restricts our ability to simulate future climate with any degree of confidence in the accuracy of the results.
- Climate models have failed to accurately reproduce observed patterns and magnitudes of various other important climate-related parameters.
- Numerous scientific studies suggest that the model-derived sensitivity accepted by the Intergovernmental Panel on Climate Change (IPCC) is far too large, and that feedbacks in the climate system could reduce it to values that may be an *order of magnitude* smaller.
- Biologically-driven phenomena could totally compensate for the warming influence of all anthropogenic CO<sub>2</sub> emissions experienced to date, as well as all those that are anticipated to occur in the future.
- Numerous studies in the scientific literature suggest that the climatic cooling effect of aerosols has been underestimated. In fact, the *negative* radiative forcing of aerosols may be as large as, or larger than, the *positive* radiative forcing due to anthropogenic CO<sub>2</sub> emissions.
- Atmospheric methane has remained nearly constant since the late 1990s. This is a most important finding, because methane's contribution to anthropogenic radiative forcing, including direct and indirect effects, is about half that of CO<sub>2</sub>.
- As the air's CO<sub>2</sub> content -- and possibly its temperature -- continues to rise, we can expect to see a significant increase in the rate of methane removal from earth's atmosphere, which should help to reduce the potential for further global warming.

Warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea level. Global mean surface temperatures have risen by 0.74°C (1.3°F) over the last 100 years.

- Several glaciers have experienced little or reduced rates of melting, with some actually *advancing*, over the past quarter-century, a period of time in which it is claimed that the earth has warmed to its highest temperature of the past thousand or more years.
- Sea ice area and extent have continued to *increase* around Antarctica over the past few decades.
- Evidence shows that much of the reported thinning of Arctic sea ice that occurred in the 1990s -- *if real*-- was *not* the result of CO<sub>2</sub>-induced global warming. Rather, it was a natural consequence of changes in ice dynamics caused by an atmospheric *regime shift*, of which there have been several in decades past and will likely be several in the decades to come, totally irrespective of past or future changes in the air's CO<sub>2</sub> content. Whether *any* portion of past sea ice thinning was due to anthropogenic CO<sub>2</sub> emissions is currently unknown, for temporal variability in Arctic sea-ice behavior is simply too great to allow such a small and slowly-developing signal to be detected yet.
- The entire history of anthropogenic CO<sub>2</sub> emissions since the inception of the Industrial Revolution has had *no discernable impact* on Greenland air temperatures.

Most of the observed increase in global average temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic GHG concentrations.

- Based on a synthesis of real-world data, the claim that temperatures over the latter part of the 20th century were higher than those experienced at any other time over the past one to two millennia is found to be false. Thus, the corollary claim that anthropogenic CO<sub>2</sub> emissions from the burning of fossil fuels have caused the planet's current "unprecedented" warmth cannot be substantiated; because late 20<sup>th</sup>-century temperatures are *not* unprecedented, falling well within the range of natural millennial-scale variability. Consequently, there is no compelling reason to believe that the historical rise in the atmosphere's CO<sub>2</sub> concentration had any significant impact on 20<sup>th</sup> century temperatures, since it was warmer than it is now fully 1000 years ago, when there was 25% less CO<sub>2</sub> in the air than there is today.

Widespread changes in extreme temperatures have been observed in the last 50 years across all world regions including the U.S.

- Air temperature variability almost always *decreases* when mean air temperature *rises*, be it in cases of temperature change over tens of thousands of years or over mere decades, or even between individual cooler and warmer years when different ENSO states are considered. The claim that global warming will lead to more extremes of

climate and weather, including more extremes of temperature itself, is not supported by real-world data.

**Observations show that changes are occurring in the amount, intensity, frequency and type of precipitation.**

- There is no support for the model-based projection that precipitation in a warming world becomes more variable and intense. In fact, some observational data suggest just the opposite, and provide support for the proposition that precipitation responds more to cyclical variations in solar activity than to anything else.

**Intensity of precipitation events is projected to increase in the U.S. and other regions of the world, increasing the risk of flooding, greater runoff and erosion, and thus the potential for adverse water quality effects.**

- Claims of floods and droughts becoming more extreme and erratic in response to global warming are not supported by real-world observations. If anything, the data tend to suggest just the *opposite*.
- In the vast majority of cases, observed trends in streamflow characteristics appear to be just the *opposite* of what is predicted to occur by climate models, leading to less frequent and severe flood and drought conditions.
- Studies of observed frequencies and maximum intensities of tropical cyclones show no consistent upward trend. In fact, many studies have actually found yearly hurricane numbers to *decline* as temperatures rise.

**There is strong evidence that global sea level gradually rose in the 20th century and is currently rising at an increased rate.**

- The mean rate of global sea level rise has *not* accelerated over the recent past. If anything, it's done just the *opposite*.

**By the end of the century, sea level is projected to rise between 0.18 and 0.59 meters relative to around 1990.**

- There is considerable uncertainty associated with a number of basic parameters that are related to the water balance of the world's oceans and the meltwater contribution of Greenland and Antarctica; and until these uncertainties are satisfactorily resolved, we cannot be confident that we know what is happening in terms of phenomena related to the vertical displacement of the upper surface of the world's oceans.

**Sea level is rising along much of the U.S. coast, and the rate of change will increase in the future, exacerbating the impacts of progressive inundation, storm-surge flooding, and shoreline erosion. Storm impacts are likely to be more severe ...**

- As the earth has warmed over the past hundred and fifty years, during its recovery from the global chill of the Little Ice Age, there has been no significant increase in either the frequency or intensity of stormy weather. In fact, most studies suggest just the *opposite* has likely occurred.
- Storm surges have definitely *not* increased in either frequency or magnitude. In the majority of cases investigated, in fact, they have actually tended to decrease.

**Climate warming may increase the possibility of large, abrupt, and unwelcome regional or global climatic events (e.g., disintegration of the Greenland Ice Sheet or collapse of the West Antarctic Ice Sheet).**

- The results of several research studies argue strongly against predictions of future catastrophic disintegration of the Greenland or Antarctic Ice Sheet caused by CO<sub>2</sub>-induced global warming. In fact, in the case of Antarctica, they suggest just the *opposite*, i.e., that CO<sub>2</sub>-induced global warming would tend to *buffer* the world against such an outcome.

**Severe heat waves are projected to intensify in magnitude and duration over the portions of the U.S. where these events already occur, with likely increases in mortality and morbidity, especially among the elderly, young and frail.**

- Global warming will likely *reduce* the number of lives lost to extreme thermal conditions, as many more people die from unseasonably cold temperatures than from excessive warmth.
- Global warming reduces the incidence of cardiovascular disease related to low temperatures and wintry weather by a much greater degree than it increases the incidence of cardiovascular disease associated with high temperatures and summer heat waves.
- Claims of malaria expanding across the globe and intensifying *as a result of CO<sub>2</sub>-induced warming* are not supported in the scientific literature.
- There is ample reason to believe that the historical increase in the air's CO<sub>2</sub> content has played a prominent role in enhancing many aspects of human health over the course of the Industrial Revolution, and that its continued upward trend will provide ever more of the same benefits, not the least of which is *increased longevity*.

- From what has been learned about plant proteins, antioxidants and the few medicinal substances that have been investigated, there is ample evidence to suggest they may well be present in significantly *greater* concentrations, and *certainly* in greater *absolute amounts* in a CO<sub>2</sub>-enriched world of the future than they are currently.

**Disturbances like wildfire ... are increasing and are likely to intensify in a warmer future with drier soils and longer growing seasons.**

- Although one can readily identify specific parts of the planet that have experienced both significant increases and decreases in land area burned over the last two to three decades of the 20th century, *for the globe as a whole* there was absolutely *no* relationship between global warming and total area burned over this latter period, during which time it is claimed the world warmed at a rate and to a degree that were both unprecedented over the past several millennia.

**Moderate climate change in the early decades of the century is projected to increase aggregate yields of rainfed agriculture by 5-20% in the U.S., but with important variability among regions.**

- A 300-ppm increase in the air's CO<sub>2</sub> content typically raises the productivity of most herbaceous plants by about *one-third*; and this positive response occurs in plants that utilize all three of the major biochemical pathways (C<sub>3</sub>, C<sub>4</sub>, CAM) of photosynthesis. For woody plants, the response is even *greater*.
- The productivity benefits of CO<sub>2</sub> enrichment are also experienced by aquatic plants, including freshwater algae and macrophytes, and marine microalgae and macroalgae.
- Although atmospheric CO<sub>2</sub> enrichment tends to increase the growth of plants under a wide range of soil nitrogen concentrations, including some that are very low, considerably greater CO<sub>2</sub>-induced enhancements are possible when more soil nitrogen is available.
- The ongoing rise in the air's CO<sub>2</sub> content is a powerful antidote for the deleterious biological impacts that might possibly be caused by an increase in the flux of UV-B radiation at the surface of the earth due to any further depletion of the planet's stratospheric ozone layer.
- Many peer-reviewed studies suggest that as the CO<sub>2</sub> content of the air rises, plants may not necessarily exhibit photosynthetic acclimation, even under conditions of low soil nitrogen; for if a plant can maintain a balance between its sources and sinks for carbohydrates at the whole-plant level, acclimation should not be necessary. In addition, because earth's atmospheric CO<sub>2</sub> content is rising by an average of only 1.5 ppm per year, most plants should be able to either (1) adjust their relative growth rates by the small amount that would be needed to prevent low nitrogen-induced acclimation from ever occurring, or (2) expand their root systems by the small amount that would

be needed to supply the extra nitrogen required to take full advantage of the CO<sub>2</sub>-induced increase in leaf carbohydrate production. However, in the event that a plant cannot initially balance its sources and sinks for carbohydrates at the whole-plant level, CO<sub>2</sub>-induced acclimation represents a beneficial secondary mechanism for achieving that balance through redistributing limiting resources away from the plant's photosynthetic machinery to strengthen sink development or enhance other nutrient-limiting processes.

- The ongoing rise in the air's CO<sub>2</sub> content likely will *not* favor the growth of weedy species over that of crops and native plants.
- The growth of plants is generally not only enhanced by CO<sub>2</sub>-induced increases in net photosynthesis during the light period of the day, it is also enhanced by CO<sub>2</sub>-induced decreases in respiration during the dark period.
- As the air's CO<sub>2</sub> content continues to rise, earth's plants will likely respond by reducing the amount of nitrogen invested in rubisco and other photosynthetic proteins, while still maintaining enhanced rates of photosynthesis, which consequently should increase their photosynthetic nitrogen-use efficiencies. In addition, enhanced rates of photosynthetic carbon uptake invariably lead to greater biomass production, which often occurs without proportionally increasing soil nitrogen uptake and thus enhances plant nitrogen-use efficiency as well. Hence, as overall plant nitrogen-use efficiency increases with the ongoing rise in the atmosphere's CO<sub>2</sub> concentration, it is likely that plants will grow ever better on soils containing less-than-optimal levels of this important soil nutrient.
- The rising CO<sub>2</sub> content of the air will likely enhance the development of more extensive plant root systems that will extract enhanced amounts of mineral nutrients from the soils in which the plants are rooted.

**Recent studies indicate that climate change scenarios that include increased frequency of heat stress, droughts and flooding events reduce crop yields and livestock productivity beyond the impacts due to changes in mean variables alone.**

- As the air's CO<sub>2</sub> content continues to rise, plants will likely exhibit enhanced rates of photosynthesis and biomass production that will *not* be diminished by any global warming that might occur concurrently. In fact, if the ambient air temperature *rises*, the growth-promoting effects of atmospheric CO<sub>2</sub> enrichment will likely rise right along with it, becoming more and *more robust*.
- The amount of carbon plants gain per unit of water lost – or *water-use efficiency* – typically rises as the CO<sub>2</sub> content of the air rises, greatly increasing their ability to withstand drought. In addition, the CO<sub>2</sub>-induced *percentage* increase in plant biomass production is often *greater* under water-stressed conditions than it is when plants are well-watered.
- Atmospheric CO<sub>2</sub> enrichment helps ameliorate the detrimental effects of several environmental stresses on plant growth and development, including high soil salinity, high

air temperature, low light intensity and low levels of soil fertility. Elevated levels of CO<sub>2</sub> have additionally been demonstrated to reduce the severity of low temperature stress, oxidative stress, and the stress of herbivory. In fact, the percentage growth enhancement produced by an increase in the air's CO<sub>2</sub> concentration is often even greater under stressful and resource-limited conditions than it is when growing conditions are ideal.

**Climate change is expected to lead to increases in regional ozone pollution, ... tropospheric ozone has significant adverse effects on crop yields, pasture and forest growth and species composition.**

- Elevated CO<sub>2</sub> reduces, and nearly always *completely overrides*, the negative effects of ozone pollution on plant photosynthesis, growth and yield.
- The ongoing rise in the atmosphere's CO<sub>2</sub> concentration will lead to ever greater reductions in atmospheric isoprene concentrations, a highly reactive *non-methane hydrocarbon* (NMHC) that is emitted in copious quantities by vegetation and is responsible for the production of vast amounts of tropospheric ozone.

**Climate variability and change also modify the risks of pest and pathogen outbreaks.**

- Rising atmospheric CO<sub>2</sub> concentrations may reduce the frequency and severity of pest outbreaks that are detrimental to agriculture, forests and grasslands, while not seriously impacting herbivorous organisms found in natural ecosystems that are normally viewed in a more favorable light.
- The ongoing rise in the air's CO<sub>2</sub> content will *not* result in greater damage to earth's vegetation by insects inhabiting the planet. If anything, it could well *reduce* the damage they cause.
- Atmospheric CO<sub>2</sub> enrichment asserts a greater influence on *infected* as opposed to *healthy* plants. Moreover, it would appear that elevated CO<sub>2</sub> has the ability to significantly ameliorate the deleterious effects of various stresses imposed upon plants by numerous pathogenic invaders.
- Elevated CO<sub>2</sub> generally tends to reduce the negative effects of parasitic infection, so that infected host plants continue to exhibit positive growth responses to elevated CO<sub>2</sub>. Thus, it is likely that whatever the scenario with regard to parasitic infection, host plants will fare better under higher atmospheric CO<sub>2</sub> conditions than they do currently.

**Although recent climate trends have increased vegetation growth, continuing increases in disturbances are likely to limit carbon storage, facilitate invasive species, and disrupt ecosystem services.**



- CO<sub>2</sub>-induced increases in plant photosynthetic rates and biomass production will likely result in more organic carbon being returned to the soil.
- The *aerial fertilization effect* of the ongoing rise in the air's CO<sub>2</sub> concentration (which greatly enhances vegetative productivity) and its *anti-transpiration effect* (which enhances plant water-use efficiency and enables plants to grow in areas that were once too dry for them) are stimulating plant growth across the globe in places that previously were too dry or otherwise unfavorable for plant growth, leading to a significant *greening of the Earth*.
- The ongoing rise in the air's CO<sub>2</sub> content, as well as any degree of warming that might possibly accompany it, will not materially alter the rate of decomposition of the world's soil organic matter. Hence, the rate at which carbon is sequestered in the world's soils should continue to increase, as a joint function of the rate at which the productivity of earth's plants is increased by the aerial fertilization effect of the rising atmospheric CO<sub>2</sub> concentration and the rate of expansion of the planet's vegetation into drier regions of the globe that is made possible by the concomitant CO<sub>2</sub>-induced increase in vegetative water use efficiency.
- Research conducted to date strongly suggests that the CO<sub>2</sub>-induced enhancement of vegetative carbon sequestration will not be reduced by any future rise in air temperature, regardless of its cause. In fact, it is likely that in a CO<sub>2</sub>-enriched atmosphere, any increase in temperature will actually *enhance* biological carbon sequestration.
- Continued increases in the air's CO<sub>2</sub> concentration and temperature will *not* result in massive losses of carbon from earth's peatlands. Quite to the contrary, these environmental changes – if they persist – would likely work together to *enhance* carbon capture by these particular ecosystems.
- The combination of greater root growth at elevated CO<sub>2</sub> combined with a decrease in root decomposition will lead to a longer residence time of carbon in the soil and, therefore, higher carbon storage or sequestration.
- Earthworms and soil nematodes respond to increases in the air's CO<sub>2</sub> content, via a number of plant-mediated phenomena, in ways that further enhance the positive effects of atmospheric CO<sub>2</sub> enrichment on plant growth and development, while at the same time helping to sequester more carbon more securely in the soil and thereby reducing the potential for CO<sub>2</sub>-induced global warming.

**Observational evidence from all continents and most oceans shows that many natural systems are being affected by regional climate changes, particularly temperature increases.**

**Over the 21st century, changes in climate will cause species to shift north and to higher elevations and fundamentally rearrange U.S. ecosystems.**

- With respect to plants, as long as the atmosphere's CO<sub>2</sub> concentration rises in tandem with its temperature, most of them will not "feel the heat," as their physiology will

change in ways that make them better adapted to warmer conditions. Hence, although earth's plants will likely spread poleward in latitude and upward in elevation at the cold-limited boundaries of their ranges in response to a warming-induced opportunity to do so, their heat-limited boundaries will probably remain pretty much as they are now or shift only slightly. Consequently, in a world of rising atmospheric CO<sub>2</sub> concentration, the ranges of most of earth's plants will likely *expand* if the planet continues to warm, making terrestrial plant extinctions even *less* likely than they are currently.

- In response to increases in atmospheric temperature and CO<sub>2</sub> concentration, land animals tend to migrate poleward and upward, where cold temperatures prevented them from going in the past, as they follow earth's plants, while the heat-limited boundaries of their ranges are often little affected, allowing them to also expand their ranges.
- With respect to marine life – and especially that of calcifying organisms such as corals and coccolithophores – neither increases in *temperature*, nor increases in atmospheric *CO<sub>2</sub> concentration*, nor increases in both of them *together*, have had any ill effects on the important processes of calcification and growth. In fact, out in the real world of nature, these processes have actually responded *positively* to the supposedly unprecedented concomitant increases in these two parameters.

**Climate change impacts in certain regions of the world may exacerbate problems that raise humanitarian and national security issues for the U.S.**

- The aerial fertilization effect of the increase in the air's CO<sub>2</sub> content that is expected to occur by the year 2050 will be *just barely sufficient*, in the mean, to assure the agricultural productivity required to prevent mass starvation in many parts of the globe without usurping what little of the natural world would remain at that time.
- Letting the evolution of technology take its *natural* course, with respect to anthropogenic CO<sub>2</sub> emissions, would appear to be the only way we will ever be able to grow enough food to support ourselves in the year 2050 without taking unconscionable amounts of land and freshwater resources from nature and decimating the biosphere in the process.
- Growing crops for biofuel production leads to a number of unintended consequences. Not only does it limit the ability of the world's poor to purchase the food they so desperately need to sustain themselves, it does *irreparable harm* to "wild nature," as native plants and animals lose ever more habitat and freshwater resources to the biofuels enterprise, which is rapidly advancing the time of their ultimate disappearance from the face of the earth, as they are inexorably driven to extinction.

## 1. CLIMATE MODEL INADEQUACIES

Because the earth-ocean-atmosphere system is so vast and complex, it is impossible to conduct a small-scale experiment that reveals how the world's climate will change as the air's greenhouse gas concentrations continue to rise. As a result, scientists *estimate* its response using computer models that define a "virtual" earth-ocean-atmosphere system. To be of any validity, however, these models must incorporate all of the many physical, chemical and biological processes that influence climate in the real world. And they must do so *correctly*.

So how do the models perform in this regard? A review of the scientific literature reveals numerous deficiencies and shortcomings in today's state-of-the-art models, some of which deficiencies could even alter the *sign* of projected climate change. In this first chapter, we provide brief summaries of several studies that outline some of these deficiencies, arranged into three subsections of model inadequacies: radiation, clouds and precipitation.

Additional information on this topic, including reviews of climate model inadequacies not discussed here, can be found at [http://www.co2science.org/subject/m/subject\\_m.php](http://www.co2science.org/subject/m/subject_m.php) under the heading Models of Climate.

### **1.1. Radiation**

One of the most challenging and important problems facing today's general circulation models of the atmosphere is how to accurately simulate the physics of earth's radiative energy balance. Of this task, Harries (2000) says "progress is excellent, on-going research is fascinating, but we have still a great deal to understand about the physics of climate."

Warning against excessive hubris, Harries says "we must exercise great caution over the true depth of our understanding, and our ability to forecast future climate trends." As an example, he states that our knowledge of high cirrus clouds is very poor, noting that "we could easily have uncertainties of many tens of  $W\ m^{-2}$  in our description of the radiative effect of such clouds, and how these properties may change under climate forcing." This state of affairs is extremely disconcerting, especially in light of the fact that the radiative effect of a doubling the air's  $CO_2$  content is in the lower single-digit range of  $W\ m^{-2}$ , and, to quote Harries, that "uncertainties as large as, or larger than, the doubled  $CO_2$  forcing could easily exist in our modeling of future climate trends, due to uncertainties in the feedback processes." Furthermore, because of the vast complexity of the subject, Harries rightly declares that "even if [our] understanding were perfect, our ability to describe the system sufficiently well in even the largest computer models is a problem."

Illustrative of a related problem is the work of Zender (1999), who characterized the spectral, vertical, regional and seasonal atmospheric heating caused by the oxygen collision pairs  $O_2 \cdot O_2$  and  $O_2 \cdot N_2$ , which had earlier been discovered to absorb a small but significant fraction of the globally-incident solar radiation. This work revealed that these molecular collisions lead to the absorption of about  $1\ Wm^{-2}$  of solar radiation, globally and annually averaged. This discovery,

in Zender's words, "alters the long-standing view that H<sub>2</sub>O, O<sub>3</sub>, O<sub>2</sub>, CO<sub>2</sub> and NO<sub>2</sub> are the only significant gaseous solar absorbers in Earth's atmosphere," and he suggests that the phenomenon "should therefore be included in ... large-scale atmospheric models used to simulate climate and climate change." It also raises the possibility there are still other yet-to-be-discovered processes that should be included in the models that are used to simulate earth's climate, and that until we are confident there is little likelihood of further such surprises, we ought not rely too heavily on what the models of today are telling us about the climate of tomorrow.

In another revealing study, Wild (1999) compared the observed amount of solar radiation absorbed in the atmosphere over equatorial Africa with what was predicted by three general circulation models of the atmosphere, finding that the model predictions were much too small. Indeed, regional and seasonal model underestimation biases were as high as  $30 \text{ Wm}^{-2}$ , primarily because the models failed to properly account for spatial and temporal variations in atmospheric aerosol concentrations. In addition, Wild found that the models likely underestimated the amount of solar radiation absorbed by water vapor and clouds.

Similar large model underestimations were discovered by Wild and Ohmura (1999), who analyzed a comprehensive observational dataset consisting of solar radiation fluxes measured at 720 sites across the earth's surface and corresponding top-of-the-atmosphere locations to assess the true amount of solar radiation absorbed within the atmosphere. These results were compared with estimates of solar radiation absorption derived from four atmospheric general circulation models (GCMs); and, again, it was shown that "GCM atmospheres are generally too transparent for solar radiation," as they produce a rather substantial mean error close to 20% below actual observations.

Another solar-related deficiency of state-of-the-art GCMs is their failure to properly account for solar-driven variations in earth-atmosphere processes that operate over a range of timescales extending from the 11-year solar cycle to century- and millennial-scale cycles (see several of the subheadings under Solar Effects in our Subject Index). Although the absolute solar flux variations associated with these phenomena are rather small, there are a number of "multiplier effects" that may significantly amplify their impacts.

According to Chambers *et al.* (1999), most of the many nonlinear responses to solar activity variability are inadequately represented (in fact, they are essentially ignored) in the global climate models used by the Intergovernmental Panel on Climate Change (IPCC) to predict future greenhouse gas-induced global warming, while at the same time *other* amplifier effects are used to model past glacial/interglacial cycles and even the hypothesized CO<sub>2</sub>-induced warming of the future, where CO<sub>2</sub> is *not* the major cause of the predicted temperature increase but rather an initial perturber of the climate system that according to the IPCC sets other more powerful forces in motion that produce the bulk of the ultimate warming. Hence, there appears to be a *double standard* within the climate modeling community that may best be described as an inherent reluctance to deal even-handedly with different aspects of climate

change. When multiplier effects suit their purposes, they use them; but when they don't suit their purposes, they don't use them.

In setting the stage for the next study of climate model inadequacies related to radiative forcing, Ghan *et al.* (2001) state that "present-day radiative forcing by anthropogenic greenhouse gases is estimated to be 2.1 to 2.8  $\text{Wm}^{-2}$ ; the direct forcing by anthropogenic aerosols is estimated to be -0.3 to -1.5  $\text{Wm}^{-2}$ , while the indirect forcing by anthropogenic aerosols is estimated to be 0 to -1.5  $\text{Wm}^{-2}$ ," so that "estimates of the total global mean present-day anthropogenic forcing range from 3  $\text{Wm}^{-2}$  to -1  $\text{Wm}^{-2}$ ," which implies a climate change somewhere between a modest warming and a slight cooling, which would seem to be a rather shaky justification for mandating draconian measures to combat the first of these possibilities. Hence, they say that *clearly* "the great uncertainty in the radiative forcing must be reduced if the observed climate record is to be reconciled with model predictions and if estimates of future climate change are to be useful in formulating emission policies."

Pursuit of this goal, as they describe it, requires achieving "profound reductions in the uncertainties of direct and indirect forcing by anthropogenic aerosols," which is what they set out to do in their analysis of the situation, which consisted of "a combination of process studies designed to improve understanding of the key processes involved in the forcing, closure experiments designed to evaluate that understanding, and integrated models that treat all of the necessary processes together and estimate the forcing." At the conclusion of this laborious set of operations, Ghan *et al.* came up with some numbers that considerably reduced the range of uncertainty in the "total global mean present-day anthropogenic forcing," but that still implied a set of climate changes stretching from a small cooling to a modest warming. Hence, they provided a long list of *other* things that must be done in order to obtain a more definitive result, after which they acknowledged that even *this* list "is hardly complete." In fact, they concluded their analysis by saying "one could easily add the usual list of uncertainties in the representation of clouds, etc." Consequently, the bottom line, in their words, is that "much remains to be done before the estimates are reliable enough to base energy policy decisions upon."

Also studying the aerosol-induced radiative forcing of climate were Vogelmann *et al.* (2003), who report that "mineral aerosols have complex, highly varied optical properties that, for equal loadings, can cause differences in the surface IR flux between 7 and 25  $\text{Wm}^{-2}$  (Sokolik *et al.*, 1998)," but who say that "only a few large-scale climate models currently consider aerosol IR effects (e.g., Tegen *et al.*, 1996; Jacobson, 2001) despite their potentially large forcing." Because of these facts, and in an attempt to persuade climate modelers to rectify the situation, Vogelmann *et al.* used high-resolution spectra to calculate the surface IR radiative forcing created by aerosols encountered in the outflow of air from northeastern Asia, based on measurements made by the Marine-Atmospheric Emitted Radiance Interferometer aboard the NOAA Ship *Ronald H. Brown* during the Aerosol Characterization Experiment-Asia. In doing so, they determined, in their words, that "daytime surface IR forcings are often a few  $\text{Wm}^{-2}$  and can reach almost 10  $\text{Wm}^{-2}$  for large aerosol loadings," which values they say "are comparable to or larger than the 1 to 2  $\text{Wm}^{-2}$  change in the globally averaged surface IR forcing caused by

greenhouse gas increases since pre-industrial times." In a massive understatement of fact, the researchers thus concluded that their results "highlight the importance of aerosol IR forcing which should be included in climate model simulations," causing us to wonder that if a forcing of this magnitude is not included in current state-of-the-art climate models, what other major forcings are they ignoring?

Shifting gears just a bit, two papers published one year earlier in the same issue of *Science* (Chen *et al.*, 2002; Wielicki *et al.*, 2002) revealed what Hartmann (2002) called a pair of "tropical surprises." The first of the seminal discoveries was the common finding of both groups of researchers that the amount of thermal radiation emitted to space at the top of the tropical atmosphere increased by about  $4 \text{ Wm}^{-2}$  between the 1980s and the 1990s, while the second was that the amount of reflected sunlight decreased by 1 to  $2 \text{ Wm}^{-2}$  over the same period, with the net result that more total radiant energy exited the tropics in the latter decade. In addition, the measured thermal radiative energy loss at the top of the tropical atmosphere was of the same magnitude as the thermal radiative energy gain that is generally predicted to result from an instantaneous doubling of the air's  $\text{CO}_2$  content. Yet as Hartman correctly notes, "only very small changes in average tropical surface temperature were observed during this time." So what went wrong? Or, as we probably more correctly should phrase the question, what went *right*?

One thing was the change in solar radiation reception that was driven by changes in cloud cover, which allowed more solar radiation to reach the surface of the earth's tropical region and warm it. These changes were produced by what Chen *et al.* determined to be "a decadal-time-scale strengthening of the tropical Hadley and Walker circulations." Another helping-hand was likely provided by the past quarter-century's slowdown in the meridional overturning circulation of the upper 100 to 400 meters of the tropical Pacific Ocean (McPhaden and Zhang, 2002), which circulation slowdown also promotes tropical sea surface warming by reducing the rate-of-supply of relatively colder water to the region of equatorial upwelling.

So what do these observations have to do with evaluating the ability of climate models to correctly predict the future? For one thing, they provide several new phenomena for the models to replicate as a test of their ability to properly represent the real-world. In the words of McPhaden and Zhang, the time-varying meridional overturning circulation of the upper Pacific Ocean provides "an important dynamical constraint for model studies that attempt to simulate recent observed decadal changes in the Pacific." If the climate models can't reconstruct this simple wind-driven circulation, for example, why should we believe anything else they tell us?

In an eye-opening application of this principle, Wielicki *et al.* tested the ability of four state-of-the-art climate models and one weather assimilation model to reproduce the observed decadal changes in top-of-the-atmosphere thermal and solar radiative energy fluxes that occurred over the past two decades. The results were truly pathetic. No significant decadal variability was exhibited by *any* of the models; and they *all* failed to reproduce even the cyclical seasonal change in tropical albedo. The administrators of the test thus kindly concluded that "the

missing variability in the models highlights the critical need to improve cloud modeling in the tropics so that prediction of tropical climate on interannual and decadal time scales can be improved." Hartmann, on the other hand, was considerably more candid in his scoring of the test, saying that the results indicated "the models are deficient." Expanding on this assessment, he further noted that "if the energy budget can vary substantially in the absence of obvious forcing," as it did over the past two decades, "then the climate of earth has modes of variability that are not yet fully understood and cannot yet be accurately represented in climate models," which leads us to wonder why anyone would put any faith in them. To do so is simply illogical.

Also concentrating on the tropics, Bellon *et al.* (2003) note that "observed tropical sea-surface temperatures (SSTs) exhibit a maximum around 30°C," and that "this maximum appears to be robust on various timescales, from intraseasonal to millennial." Hence, they say that "identifying the stabilizing feedback(s) that help(s) maintain this threshold is essential in order to understand how the tropical climate reacts to an external perturbation," which knowledge is needed for understanding how the *global* climate reacts to perturbations such as those produced by solar variability and the ongoing rise in the air's CO<sub>2</sub> content. This contention is further substantiated by the study of Pierrehumbert (1995), which "clearly demonstrates," in the words of Bellon *et al.*, "that the tropical climate is not determined locally, but globally." Also, they note that Pierrehumbert's work demonstrates that interactions between moist and dry regions are an essential part of tropical climate stability, which harkens back to the *adaptive infrared iris concept* of Lindzen *et al.* (2001).

Noting that previous box models of tropical climate have shown it to be rather sensitive to the relative areas of moist and dry regions of the tropics, Bellon *et al.* analyzed various feedbacks associated with this sensitivity in a four-box model of the tropical climate "to show how they modulate the response of the tropical temperature to a radiative perturbation." In addition, they investigated the influence of the model's surface-wind parameterization in an attempt to shed further light on the nature of the underlying feedbacks that help define the global climate system that is responsible for the tropical climate observations of constrained maximum SSTs.

Bellon *et al.*'s work, as they describe it, "suggests the presence of an important and as-yet-unexplored feedback in earth's tropical climate, that could contribute to maintain the 'lid' on tropical SSTs," much like the adaptive infrared iris concept of Lindzen *et al.* does. They also say that the demonstrated "dependence of the surface wind on the large-scale circulation has an important effect on the sensitivity of the tropical system," specifically stating that "this dependence reduces significantly the SST sensitivity to radiative perturbations by enhancing the evaporation feedback," which injects more heat into the atmosphere and allows the atmospheric circulation to export more energy to the subtropical free troposphere, where it can be radiated to space. Clearly, therefore, the case is not closed on either the *source* or the *significance* of the maximum "allowable" SSTs of tropical regions; and, hence, neither is the case closed on the degree to which the planet may warm in response to continued increases in the atmospheric concentrations of carbon dioxide and other greenhouse gases, in stark contrast to what is suggested by the climate models promoted by the IPCC.

In conclusion, there appear to be a number of major inadequacies in the ways in which several aspects of earth's radiative energy balance are treated in contemporary general circulation models of the atmosphere, as well as numerous other telling inadequacies stemming from the *non*-treatment of pertinent phenomena that are nowhere to be found in the models. Hence, there is no rational basis for any of the IPCC-inspired predictions of catastrophic climatic changes due to continued anthropogenic CO<sub>2</sub> emissions. The many scenarios they promulgate are simply unwarranted projections that have far outpaced what can be soundly supported by the current state of the climate modeling enterprise.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/m/inadegradiation.php>.

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## 1.2. Clouds

Correctly parameterizing the influence of clouds on climate is an elusive goal that the creators of atmospheric general circulation models (GCMs) have yet to achieve. One reason for their lack of success in this endeavor has to do with model resolution on both vertical and horizontal space scales. Lack of adequate resolution forces modelers to parameterize the ensemble large-scale effects of processes that occur on smaller scales than their models' are capable of handling. This is particularly true of physical processes such as cloud formation and cloud-radiation interactions. It is only natural to wonder, therefore, if the parameterizations used in the models that prompted calls for severe cuts in anthropogenic CO<sub>2</sub> emissions over the past decade or so adequately represented these processes and their interactions. The results of several studies conducted near the turn of the past century suggest that model parameterizations of that period did *not* succeed in this regard (Groisman *et al.*, 2000); and subsequent studies suggest that they are *still* not succeeding.

Lane *et al.* (2000), for example, evaluated the sensitivities of the cloud-radiation parameterizations utilized in contemporary GCMs to changes in vertical model resolution, varying the latter from 16 to 60 layers in increments of four and comparing the results to

observed values. This effort revealed that cloud fraction varied by approximately 10% over the range of resolutions tested, which corresponded to about 20% of the observed cloud cover fraction. Similarly, outgoing longwave radiation varied by 10 to 20  $\text{Wm}^{-2}$  as model vertical resolution was varied, amounting to approximately 5 to 10% of observed values, while incoming solar radiation experienced similar significant variations across the range of resolutions tested. What is more, the model results did not converge, even at a resolution of 60 layers.

In an analysis of the multiple roles played by cloud microphysical processes in determining tropical climate, Grabowski (2000) found much the same thing, noting there were serious problems related to the degree to which computer models failed to correctly incorporate cloud microphysics. These observations led him to conclude that "it is unlikely that traditional convection parameterizations can be used to address this fundamental question in an effective way." He also became convinced that "classical convection parameterizations do not include realistic elements of cloud physics and they represent interactions among cloud physics, radiative processes, and surface processes within a very limited scope." Consequently, he but stated the obvious when he concluded that "model results must be treated as qualitative rather than quantitative."

Reaching rather similar conclusions were Gordon *et al.* (2000), who determined that many GCMs of the late 1990s tended to under predict the presence of subtropical marine stratocumulus clouds, and that they failed to simulate the seasonal cycle of the clouds. These deficiencies are extremely important, because these particular clouds exert a major cooling influence on the surface temperatures of the sea below them. In the situation investigated Gordon and his colleagues, for example, the removal of the low clouds, as occurred in the normal application of their model, led to sea surface temperature increases on the order of 5.5°C.

Further condemnation of turn-of-the-century model treatments of clouds came from Harries (2000), who wrote that our knowledge of high cirrus clouds is very poor and that "we could easily have uncertainties of many tens of  $\text{Wm}^{-2}$  in our description of the radiative effect of such clouds, and how these properties may change under climate forcing." This problem is particularly noteworthy in light of the fact that the radiative effect of a doubling of the air's  $\text{CO}_2$  content is only on the order of low single-digit  $\text{Wm}^{-2}$ . It is, therefore, truly an understatement to say, as Harries did, that "uncertainties as large as, or larger than, the doubled  $\text{CO}_2$  forcing could easily exist in our modeling of future climate trends, due to uncertainties in the feedback processes."

Moving into the 21st century, Lindzen *et al.* (2001) analyzed cloud cover and sea surface temperature (SST) data over a large portion of the Pacific Ocean, finding a strong inverse relationship between upper-level cloud area and mean SST, such that the area of cirrus cloud coverage normalized by a measure of the area of cumulus coverage decreased by about 22% for each degree C increase in cloudy region SST. *Essentially*, as the researchers described it, "the cloudy-moist region appears to act as an infrared adaptive iris that opens up and closes

down the regions free of upper-level clouds, which more effectively permit infrared cooling, in such a manner as to resist changes in tropical surface temperature." The sensitivity of this negative feedback was calculated by Lindzen *et al.* to be substantial. In fact, they estimated it would "more than cancel all the positive feedbacks in the more sensitive current climate models" that were being used to predict the consequences of projected increases in atmospheric CO<sub>2</sub> concentration. And, as one might suppose, evidence of this potential impediment to global warming was nowhere to be seen *then*, and is nowhere to be seen *now*, even in today's most advanced GCMs.

Clearly, this challenge to climatic *political* correctness could not go uncontested; and Hartmann and Michelsen (2002) quickly claimed that the correlation noted by Lindzen *et al.* resulted from variations in subtropical clouds that are not physically connected to deep convection near the equator, and that it was thus "unreasonable to interpret these changes as evidence that deep tropical convective anvils contract in response to SST increases." Fu *et al.* (2002) also chipped away at the adaptive infrared iris concept, arguing that "the contribution of tropical high clouds to the feedback process would be small since the radiative forcing over the tropical high cloud region is near zero and not strongly positive," while also claiming to show that water vapor and low cloud effects were overestimated by Lindzen *et al.* by at least 60% and 33%, respectively." As a result, they obtained a feedback factor in the range of -0.15 to -0.51, compared to Lindzen *et al.*'s much larger negative feedback factor of -0.45 to -1.03.

In a contemporaneously published reply to this critique, Chou *et al.* (2002) stated that Fu *et al.*'s approach of specifying longwave emission and cloud albedos "appears to be inappropriate for studying the iris effect," and that since "thin cirrus are widespread in the tropics and ... low boundary clouds are optically thick, the cloud albedo calculated by [Fu *et al.*] is too large for cirrus clouds and too small for boundary layer clouds," so that "the near-zero contrast in cloud albedos derived by [Fu *et al.*] has the effect of underestimating the iris effect." In the end, however, Chou *et al.* agreed that Lindzen *et al.* "may indeed have overestimated the iris effect somewhat, though hardly by as much as that suggested by [Fu *et al.*]."

Although there has thus been some convergence in the two extreme views of the subject, the debate over the reality and/or magnitude of the adaptive infrared iris effect continues apace; and when some of the meteorological community's best minds continue to clash over the nature and magnitude of the phenomenon, it is amazing that the EPA seeks to reduce anthropogenic CO<sub>2</sub> emissions via the Clean Air Act, as if the issue were settled when it clearly is not.

This situation is illustrative of the importance of the advice given two years earlier by Grassel (2000), who in a review of the then-current status of the climate modeling enterprise noted that changes in many climate-related phenomena, including cloud optical and precipitation properties caused by changes in the spectrum of cloud condensation nuclei, were insufficiently well known to provide useful insights into future conditions. His advice in the light of this knowledge gap was that "we must continuously evaluate and improve the GCMs we use,"

although he was forced to acknowledge that contemporary climate model results were already being "used by many decision-makers, including governments."

This state of affairs has continued to the present day and is very disturbing, as national and international policy is being made on the basis of vastly imperfect mathematical representations of a whole host of physical, chemical and biological phenomena, many of which involve clouds. Although some may think that what we currently know about the subject is sufficient for predictive purposes, a host of questions posed by Grassl - for which we *still* lack definitive answers - demonstrates that this assumption is erroneous.

As but a single example, Charlson *et al.* (1987) described a negative feedback process that links biologically-produced dimethyl sulfide (DMS) in the oceans with climate. The basic tenant of this hypothesis derives from the fact that the global radiation balance is significantly influenced by the albedo of marine stratus clouds, and that the albedo of these clouds is a function of cloud droplet concentration, which is dependent upon the availability of condensation nuclei that have their origin in the flux of DMS from the world's oceans to the atmosphere.

Acknowledging that the roles played by DMS oxidation products within the context described above are indeed "diverse and complex" and in many instances "not well understood," Ayers and Gillett (2000) summarized empirical evidence supporting Charlson *et al.*'s hypothesis that was derived from data collected at Cape Grim, Tasmania, and from reports of other pertinent studies in the peer-reviewed scientific literature. According to their findings, the "major links in the feedback chain proposed by Charlson *et al.* (1987) have a sound physical basis," and there is "compelling observational evidence to suggest that DMS and its atmospheric products participate significantly in processes of climate regulation and reactive atmospheric chemistry in the remote marine boundary layer of the Southern Hemisphere."

The empirical evidence analyzed by Ayers and Gillett (see also, in this regard, Dimethyl Sulfide in our Subject Index) highlights an important suite of negative feedback processes that act in opposition to model-predicted CO<sub>2</sub>-induced global warming over the world's oceans; and these processes are not fully incorporated into even the very best of the current crop of climate models, nor are analogous phenomena that occur over land included in them, such as those discussed by Idso (1990).

Further to this point, O'Dowd *et al.* (2004) measured size-resolved physical and chemical properties of aerosols found in northeast Atlantic marine air arriving at the Mace Head Atmospheric Research station on the west coast of Ireland during phytoplanktonic blooms at various times of the year. In doing so, they found that in the winter, when biological activity was at its lowest, the organic fraction of the submicrometer aerosol mass was about 15%. During the spring through autumn, however, when biological activity was high, they found that "the organic fraction dominates and contributes 63% to the submicrometer aerosol mass (about 45% is water-insoluble and about 18% water-soluble)." Based on these findings, they performed model simulations that indicated that the marine-derived organic matter "can

enhance the cloud droplet concentration by 15% to more than 100% and is therefore an important component of the aerosol-cloud-climate feedback system involving marine biota."

As for the significance of their findings, O'Dowd *et al.* state that their data "completely change the picture of what influences marine cloud condensation nuclei given that water-soluble organic carbon, water-insoluble organic carbon and surface-active properties, all of which influence the cloud condensation nuclei activation potential, are typically not parameterized in current climate models," or as they say in another place in their paper, "an important source of organic matter from the ocean is omitted from current climate-modeling predictions and should be taken into account."

Another perspective on the cloud-climate conundrum is provided by Randall *et al.* (2003), who state at the outset of their review of the subject that "the representation of cloud processes in global atmospheric models has been recognized for decades as the source of much of the uncertainty surrounding predictions of climate variability." They report, however, that "despite the best efforts of [the climate modeling] community ... the problem remains largely unsolved." What is more, they say that "at the current rate of progress, cloud parameterization deficiencies will continue to plague us for many more decades into the future."

So what's the problem? "Clouds are complicated," Randall *et al.* declare, as they begin to describe what they call the "appalling complexity" of the cloud parameterization situation. For starters, they state that "our understanding of the interactions of the hot towers [of cumulus convection] with the global circulation is still in a fairly primitive state," and not knowing all that much about *what goes up*, it's not surprising that we also don't know all that much about *what comes down*, as they report that "downdrafts are either not parameterized or crudely parameterized in large-scale models."

With respect to stratiform clouds, the situation is no better, as their parameterizations are described by Randall *et al.* as "very rough caricatures of reality." As for *interactions* between convective and stratiform clouds, *forget about it* ... which is pretty much what scientists themselves did during the 1970s and 80s, when Randall *et al.* report that "cumulus parameterizations were extensively tested against observations without even accounting for the effects of the attendant stratiform clouds." Even at the time of their study, in fact, they had to report that the concept of detrainment was "somewhat murky," and that the conditions that trigger detrainment were "imperfectly understood." Hence, it should again come as no surprise that "at this time," as they put it, "no existing GCM includes a satisfactory parameterization of the effects of mesoscale cloud circulations."

Randall *et al.* additionally say that "the large-scale effects of microphysics, turbulence, and radiation should be parameterized as closely coupled processes acting in concert," but they report that only a few GCMs have even *attempted* to do so. Why? Because, as they continue, "the cloud parameterization problem is overwhelmingly complicated," and "cloud parameterization developers," as they call them, are *still* "struggling to identify the most important processes on the basis of woefully incomplete observations." To drive this point

home, they say "there is little question why the cloud parameterization problem is taking a long time to solve: It is very, very hard." In fact, the four scientists conclude that "a sober assessment suggests that with current approaches the cloud parameterization problem will not be 'solved' in any of our lifetimes."

With such a bleak assessment of where the climate-modeling community currently stands with respect to just *the single issue of cloud parameterization*, it might be well to pause and ask how anyone could possibly feel confident about what even the best climate models of the day are predicting about CO<sub>2</sub>-induced global warming, *where proper cloud responses are critical to reaching a correct conclusion*. However, a shining hope of the climate-modeling community of tomorrow resides, according to Randall *et al.*, in something called "cloud system-resolving models" or CSRMs, which can be compared with single-column models or SCMs that can be "surgically extracted from their host GCMs." These advanced models, as they describe them, "have resolutions fine enough to represent individual cloud elements, and space-time domains large enough to encompass many clouds over many cloud lifetimes." Of course, these improvements mean that "the computational cost of running a CSRMs is hundreds or thousands of times greater than that of running an SCM." Nevertheless, in a few more *decades*, according to Randall *et al.*, "it will become possible to use such global CSRMs to perform century-scale climate simulations, relevant to such problems as anthropogenic climate change."

A few more decades, however, is a little long to wait to address an issue we are confronting now. Hence, Randall *et al.* say that an approach that could be used very soon (to possibly determine whether or not there even is a problem) is to "run a CSRMs as a 'superparameterization' inside a GCM," which configuration they call a "super-GCM." Not wanting to be accused of impeding scientific progress, we say "go for it," but only with the proviso that if we are going to spend so much money on the project and devote so many scientific careers to it, we should admit up front that it is truly *needed* in order to obtain a definitive answer to the question of CO<sub>2</sub>-induced "anthropogenic climate change." And admitting such, we should not do anything rash in the interim in an expensive and likely futile attempt to alter the course of future climate.

So it comes down to this: either we know enough about how the world's climate system works, so that we don't need the postulated super-GCMs, or we *don't* know enough about how it works and we *do* need them. We happen to believe with Randall *et al.* that our knowledge of *many* aspects of earth's climate system is *sadly* deficient. So let's own up to that fact and openly admit that we currently have *no rational basis* for implementing programs designed to restrict anthropogenic CO<sub>2</sub> emissions. The cloud parameterization problem *by itself* is so complex that no one can validly claim that humanity's continued utilization of fossil-fuel energy will result in massive counter-productive climatic changes. There is absolutely no justification for that conclusion in *reliable* theoretical models, simply because *there are none*.

That the basis for this conclusion is robust, and cannot be said to rest on the less-than-enthusiastic remarks of a handful of exasperated climate modelers, we report the results of additional studies of the subject that were published *subsequent* to the analysis of Randall *et*

*al.*, and which therefore could have readily refuted their assessment of the situation if they felt that such was appropriate.

In the first of these studies, which was conducted by *seventeen other climate modelers*, Siebesma *et al.* (2004) report that "simulations with nine large-scale models [were] carried out for June/July/August 1998 and the quality of the results [was] assessed along a cross-section in the subtropical and tropical North Pacific ranging from (235°E, 35°N) to (187.5°E, 1°S)," in order to "document the performance quality of state-of-the-art GCMs in modeling the first-order characteristics of subtropical and tropical cloud systems." The *main conclusions* of this study, according to Siebesma *et al.*, were that "(1) almost all models strongly underpredicted both cloud cover and cloud amount in the stratocumulus regions while (2) the situation is opposite in the trade-wind region and the tropics where cloud cover and cloud amount are overpredicted by most models." In fact, they report that "these deficiencies result in an overprediction of the downwelling surface short-wave radiation of typically  $60 \text{ W m}^{-2}$  in the stratocumulus regimes and a similar underprediction of  $60 \text{ W m}^{-2}$  in the trade-wind regions and in the intertropical convergence zone (ITCZ)," which discrepancies are to be compared with a radiative forcing of only a couple of  $\text{W m}^{-2}$  for a 300-ppm increase in the atmosphere's  $\text{CO}_2$  concentration. In addition, they state that "similar biases for the short-wave radiation were found at the top of the atmosphere, while discrepancies in the outgoing long-wave radiation are most pronounced in the ITCZ."

The seventeen scientists, who hail from nine different countries, also state that "the representation of clouds in general-circulation models remains one of the most important as *yet unresolved* [our italics] issues in atmospheric modeling." This is partially due, they continue, "to the overwhelming variety of clouds observed in the atmosphere, but even more so due to the large number of physical processes governing cloud formation and evolution as well as the great complexity of their interactions." Hence, they conclude that through repeated critical evaluations of the type they conducted, "the scientific community will be forced to develop further physically sound parameterizations that *ultimately* [our italics] result in models that are capable of simulating our climate system with increasing realism." Until that time (indeed, until climate simulations can be done, not with *increasing* realism, but with *true* realism), we suggest that it is not wise to put much credence in what these admittedly inadequate state-of-the-art GCMs suggest about the future; and to actually *mandate* drastic reductions in fossil-fuel energy use on the basis of what these models currently suggest can only be described as downright foolish.

In an effort to assess the status of state-of-the-art climate models in simulating cloud-related processes, Zhang *et al.* (2005) compared basic cloud climatologies derived from ten atmospheric GCMs with satellite measurements obtained from the International Satellite Cloud Climatology Project (ISCCP) and the Clouds and Earth's Radiant Energy System (CERES) program. ISCCP data were available from 1983 to 2001, while data from the CERES program were available for the winter months of 2001 and 2002 and for the summer months of 2000 and 2001. The purpose of their analysis was two-fold: (1) to assess the current status of climate

models in simulating clouds so that future progress can be measured more objectively, and (2) to reveal serious deficiencies in the models so as to improve them.

The work of the *twenty additional climate modelers* involved in this exercise reveals a huge list of major model imperfections. First, Zhang *et al.* report a four-fold difference in high clouds among the models, and that the majority of the models only simulated 30-40% of the observed middle clouds, with some models simulating less than a quarter of observed middle clouds. For low clouds, they report that half the models underestimated them, such that the grand mean of low clouds from all models was only 70-80% of what was observed. Furthermore, when stratified in optical thickness ranges, the majority of the models simulated optically thick clouds more than twice as frequently as was found to be the case in the satellite observations, while the grand mean of all models simulated about 80% of optically intermediate clouds and 60% of optically thin clouds. And in the case of *individual* cloud types, the group of researchers reports that "differences of seasonal amplitudes among the models and satellite measurements can reach several hundred percent." As a result of these and other observations, Zhang *et al.* conclude that "much more needs to be done to fully understand the physical causes of model cloud biases presented here and to improve the models." We agree, especially since the deficiencies they discovered have relevance to model predictions of CO<sub>2</sub>-induced global warming.

Next, L'Ecuyer and Stephens (2007) used multi-sensor observations of visible, infrared and microwave radiance obtained from the Tropical Rainfall Measuring Mission satellite for the period running from January 1998 through December 1999, in order to evaluate the sensitivity of atmospheric heating -- and the factors that modify it -- to changes in east-west sea surface temperature gradients associated with the strong 1998 El Niño event in the tropical Pacific, as expressed by the simulations of nine general circulation models of the atmosphere that were utilized in the Intergovernmental Panel on Climate Change's most recent Fourth Assessment Report. This protocol, in their words, "provides a natural example of a short-term climate change scenario in which clouds, precipitation, and regional energy budgets in the east and west Pacific are observed to respond to the eastward migration of warm sea surface temperatures."

Results indicated that "a majority of the models examined do not reproduce the apparent westward transport of energy in the equatorial Pacific during the 1998 El Niño event." They also found that "the intermodel variability in the responses of precipitation, total heating, and vertical motion is often larger than the intrinsic ENSO signal itself, implying an inherent lack of predictive capability in the ensemble with regard to the response of the mean zonal atmospheric circulation in the tropical Pacific to ENSO." In addition, they reported that "many models also misrepresent the radiative impacts of clouds in both regions [the east and west Pacific], implying errors in total cloudiness, cloud thickness, and the relative frequency of occurrence of high and low clouds." As a result of these much-less-than-adequate findings, the two researchers from Colorado State University's Department of Atmospheric Science conclude that "deficiencies remain in the representation of relationships between radiation, clouds, and



precipitation in current climate models," and they say that these deficiencies "cannot be ignored when interpreting their predictions of future climate."

In one final paper, published in the *Journal of the Atmospheric Sciences*, Zhou *et al.* (2007) state that "clouds and precipitation play key roles in linking the earth's energy cycle and water cycles," noting that "the sensitivity of deep convective cloud systems and their associated precipitation efficiency in response to climate change are key factors in predicting the future climate." They also report that *cloud resolving models* or CRMs "have become one of the primary tools to develop the physical parameterizations of moist and other subgrid-scale processes in global circulation and climate models," and that CRMs could someday be used in place of traditional cloud parameterizations in such models.

In this regard, the authors note that "CRMs still need parameterizations on scales smaller than their grid resolutions and have many known and unknown deficiencies." To help stimulate progress in these areas, therefore, the nine scientists compared the cloud and precipitation properties observed from the Clouds and the Earth's Radiant Energy System (CERES) and Tropical Rainfall Measuring Mission (TRMM) instruments against simulations obtained from the three-dimensional Goddard Cumulus Ensemble (GCE) model during the South China Sea Monsoon Experiment (SCSMEX) field campaign of 18 May-18 June 1998.

So what did the researchers learn from these efforts? Zhou *et al.* report that: (1) "the GCE rainfall spectrum includes a greater proportion of heavy rains than PR (Precipitation Radar) or TMI (TRMM Microwave Imager) observations," (2) "the GCE model produces excessive condensed water loading in the column, especially the amount of graupel as indicated by both TMI and PR observations," (3) "the model also cannot simulate the bright band and the sharp decrease of radar reflectivity above the freezing level in stratiform rain as seen from PR," (4) "the model has much higher domain-averaged OLR (outgoing longwave radiation) due to smaller total cloud fraction," (5) "the model has a more skewed distribution of OLR and effective cloud top than CERES observations, indicating that the model's cloud field is insufficient in area extent," (6) "the GCE is ... not very efficient in stratiform rain conditions because of the large amounts of slowly falling snow and graupel that are simulated," and finally, in summation, that (7) "large differences between model and observations exist in the rain spectrum and the vertical hydrometeor profiles that contribute to the associated cloud field."

In light of these several significant findings, it is clear that CRMs still have a long way to go before they are ready for "prime time" in the complex quest to properly assess the roles of *various types of clouds* and *forms of precipitation* in the future evolution of earth's climate in response to variations in numerous anthropogenic and background forcings. This evaluation is not meant to denigrate the CRMs in any way; it is merely done to indicate that the climate modeling enterprise is not yet at the stage where implicit faith should be placed in what it *currently* suggests about earth's climatic response to the ongoing rise in the air's CO<sub>2</sub> content.

In conclusion, there is absolutely no question but that the set of problems that currently restricts our ability to properly model a whole suite of cloud-related processes likewise restricts our ability to simulate future climate with any degree of confidence in the accuracy of the results.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/m/inadeqclouds.php>.

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### **1.3. Precipitation**

One of the basic predictions of atmospheric general circulation models (GCMs) is that the planet's hydrologic cycle will intensify as the world warms, leading to an increase in both the frequency and intensity of extreme precipitation events. In an early review of the subject, Walsh and Pittock (1998) reported "there is some evidence from climate model studies that, in a warmer climate, rainfall events will be more intense," and that "there is considerable evidence that the frequency of extreme rainfall events may increase in the tropics." Upon further study, however, they were forced to conclude that "because of the insufficient resolution of climate models and their generally crude representation of sub-grid scale and

convective processes, little confidence can be placed in any definite predictions of such effects."

Two years later, Lebel *et al.* (2000) compared rainfall simulations produced by a GCM with real-world observations from West Africa for the period 1960-1990. Their analysis revealed that the model output was affected by a number of temporal and spatial biases that led to significant differences between observed and modeled data. The simulated rainfall totals, for example, were significantly greater than what was typically observed, exceeding real-world values by 25% during the dry season and 75% during the rainy season. In addition, the seasonal cycle of precipitation was not well simulated, as the researchers found that the simulated rainy season began too early and that the increase in precipitation was not rapid enough. Shortcomings were also evident in the GCM's inability to accurately simulate convective rainfall events, as it typically predicted far too much precipitation. Furthermore, it was found that "interannual variability [was] seriously disturbed in the GCM as compared to what it [was] in the observations." As for *why* the GCM performed so poorly in these several respects, Lebel *et al.* gave two main reasons. They said the parameterization of rainfall processes in the GCM was much too simple and that the spatial resolution was much too coarse.

Following the passage of an additional three years, Woodhouse (2003) generated a tree-ring-based history of snow water equivalent (SWE) characteristic of the first day of April for each year of the period 1569-1999 for the drainage basin of the Gunnison River of western Colorado, USA. Then, because "an understanding of the long-term characteristics of snowpack variability is useful for guiding expectations for future variability," as she phrased it, she analyzed the reconstructed SWE data in such a way as to determine if there was there anything unusual about the SWE record of the 20th century, which hundred-year period is claimed by climate alarmists to have experienced a warming that was *unprecedented over the past two millennia*.

So did Woodhouse find anything unusual? Yes, she did. She found that "the twentieth century is notable for several periods that *lack* [our italics] extreme years." Specifically, she determined that "the twentieth century is notable for several periods that contain few or no extreme years, for both low and high SWE extremes," and she reports that "the twentieth century also contains the lowest percent of extreme low SWE years." These results, of course, are in direct contradiction of what state-of-the-art GCMs typically predict should occur in response to global warming; and their failure in this regard is especially damning, knowing it occurred during a period of global warming that is said by many have been the most significant of the past 20 centuries.

Two years later, and as a result of the fact that the 2004 summer monsoon season of India experienced a 13% precipitation deficit that was not predicted by any of the empirical or dynamical models regularly used in making rainfall forecasts, Gadgil *et al.* (2005) performed an historical analysis of the models' forecast skill over the period 1932-2004. Interestingly, and despite numerous model advancements and an ever-improving understanding of monsoon variability, they found that the models' skill in forecasting the Indian monsoon's characteristics

had not improved since the very first versions of the models were applied to the task some seven decades earlier.

In the case of the empirical models Gadgil *et al.* evaluated, large differences were generally observed between monsoon rainfall measurements and model predictions. In addition, the models often failed to correctly predict even the *sign* of the precipitation anomaly, frequently predicting excess rainfall when drought occurred and drought when excess rainfall was received.

The dynamical models fared even worse. In comparing observed monsoon rainfall totals with simulated values obtained from 20 state-of-the-art GCMs and a supposedly superior coupled atmosphere-ocean model, Gadgil *et al.* report that not a single one of these many models was able "to simulate correctly the interannual variation of the summer monsoon rainfall over the Indian region." And as with the empirical models, the dynamical models also frequently failed to correctly capture even the *sign* of the observed rainfall anomalies. In addition, the researchers report that Brankovic and Molteni (2004) attempted to model the Indian monsoon with a much higher-resolution GCM, but that its output *also* proved to be "not realistic."

Consequently, and in spite of the *billions of dollars* that have been spent by the United States alone on developing and improving climate models, taxpayers have achieved essentially *no return on their investment* in terms of the models' ability to correctly simulate one of the largest and most regionally-important of earth's atmospheric phenomena -- the tropical Indian monsoon. After more than *70 years* of trying to remake the models into better predictive tools, one would surely have expected *some* improvement in this regard, even if only by *accident*. That there has been absolutely *none* is a sad commentary indeed on the state of the climate modeling enterprise.

Advancing one more year in time, Lau *et al.* (2006) considered the Sahel drought of the 1970s-90s to provide "an ideal test bed for evaluating the capability of CGCMs [coupled general circulation models] in simulating long-term drought, and the veracity of the models' representation of coupled atmosphere-ocean-land processes and their interactions." Hence, they decided to "explore the roles of sea surface temperature coupling and land surface processes in producing the Sahel drought in CGCMs that participated in the twentieth-century coupled climate simulations of the Intergovernmental Panel on Climate Change [IPCC] Assessment Report 4," in which the 19 CGCMs "are driven by combinations of realistic prescribed external forcing, including anthropogenic increase in greenhouse gases and sulfate aerosols, long-term variation in solar radiation, and volcanic eruptions."

In performing this analysis, the climate scientists found, in their words, that "only eight models produce a reasonable Sahel drought signal, seven models produce excessive rainfall over [the] Sahel during the observed drought period, and four models show no significant deviation from normal." In addition, they report that "even the model with the highest skill for the Sahel drought could only simulate the increasing trend of severe drought events but not the magnitude, nor the beginning time and duration of the events." Consequently, since all 19 of

the CGCMs employed in the IPCC's Fourth Assessment Report failed to adequately simulate the basic characteristics of "one of the most pronounced signals of climate change" of the past century -- as defined by its start date, severity and duration -- the results of this "ideal test" for evaluating the models' capacity for accurately simulating "long-term drought" and "coupled atmosphere-ocean-land processes and their interactions" would almost *mandate* that it would be unwise to rely on their output as a guide to the future, especially when the tested models were "driven by combinations of realistic prescribed external forcing" and they *still* could not properly simulate the past.

During the following year of 2007, a number of other pertinent papers appeared. In an intriguing report in *Science*, Wentz *et al.* (2007) noted that the Coupled Model Intercomparison Project, as well as various climate modeling analyses, predicted an increase in precipitation on the order of one to three percent per °C of surface global warming. Hence, they decided to see what had happened in the real world in this regard over the prior 19 years (1987-2006) of supposedly *unprecedented global warming*, when data from the Global Historical Climatology Network and satellite measurements of the lower troposphere indicated there had been a global temperature rise on the order of 0.20°C per decade.

Using satellite observations obtained from the Special Sensor Microwave Imager (SSM/I), the four *Remote Sensing Systems* scientists derived precipitation trends for the world's oceans over this period; and using data obtained from the Global Precipitation Climatology Project that were acquired from both satellite and rain gauge measurements, they derived precipitation trends for earth's continents. Appropriately combining the results of these two endeavors, they derived a real-world increase in precipitation on the order of 7% per °C of surface global warming, which is somewhere between 2.3 and 7 times *larger* than what is predicted by state-of-the-art climate models.

How was this horrendous discrepancy to be resolved?

Based on theoretical considerations, Wentz *et al.* concluded that the only way to bring the two results into harmony with each other was for there to have been a 19-year *decline* in global wind speeds. But when looking at the past 19 years of SSM/I wind retrievals, they found just the *opposite*, i.e., an *increase* in global wind speeds. In quantitative terms, in fact, the two results were about *as opposite as they could possibly be*, as they report that "when averaged over the tropics from 30°S to 30°N, the winds increased by 0.04 m s<sup>-1</sup> (0.6%) decade<sup>-1</sup>, and over all oceans the increase was 0.08 m s<sup>-1</sup> (1.0%) decade<sup>-1</sup>," while global coupled ocean-atmosphere models or GCMs, in their words, "predict that the 1987-to-2006 warming should have been accompanied by a decrease in winds on the order of 0.8% decade<sup>-1</sup>."

In discussing these results, Wentz *et al.* correctly state that "the reason for the discrepancy between the observational data and the GCMs is not clear." They also rightly state that this dramatic difference between the real world of nature and the virtual world of climate modeling "has enormous impact," concluding that the questions raised by the discrepancy "are far from being settled."

In another intriguing bit of research, Allan and Soden (2007) quantified trends in precipitation within ascending and descending branches of the planet's tropical circulation and compared their results with simulations of the present day and projections of future changes provided by up to 16 state-of-the-art climate models. The precipitation data for this analysis came from the Global Precipitation Climatology Project (GPCP) of Adler *et al.* (2003) and the Climate Prediction Center Merged Analysis of Precipitation (CMAP) data of Xie and Arkin (1998) for the period 1979-2006, while for the period 1987-2006 they came from the monthly mean intercalibrated Version 6 Special Sensor Microwave Imager (SSM/I) precipitation data described by Wentz *et al.* (2007).

So what did the researchers learn?

Allan and Soden report that "an emerging signal of rising precipitation trends in the ascending regions and decreasing trends in the descending regions are detected in the observational datasets," but that "these trends are substantially larger in magnitude than present-day simulations and projections into the 21st century," especially in the case of the descending regions. More specifically, they state that, for the tropics, "the GPCP trend is about 2-3 times larger than the model ensemble mean trend, consistent with previous findings (Wentz *et al.*, 2007) and also supported by the analysis of Yu and Weller (2007)," who additionally contend that "observed increases of evaporation over the ocean are substantially greater than those simulated by climate models." What is more, Allan and Soden note that "observed precipitation changes over land also appear larger than model simulations over the 20th century (Zhang *et al.*, 2007)."

What is one to make of this conflict between models and measurements?

Noting that the difference between the two "has important implications for future predictions of climate change," Allan and Soden say "the discrepancy cannot be explained by changes in the reanalysis fields used to subsample the observations but instead must relate to errors in the satellite data *or in the model parameterizations* [our italics]." This same dilemma was also faced by Wentz *et al.* (2007); and they too stated that the resolution of the issue "has enormous impact," but likewise concluded that the questions raised by the discrepancy "are far from being settled."

To us, the issue seems a bit less difficult. Given a choice between *model simulations* and *observational reality*, we will cast our lot with the latter every chance we get. Granted, this choice implies a huge problem with the former. But why should that be a surprise to anyone? The earth, with its oceans and atmosphere, and its myriad life forms, is a most complex place; and to believe that we have condensed all of its many climate-related phenomena -- many of which are shrouded in mystery, and some of which may even remain undetected -- to a set of equations that rigorously define our climatic future in response to an increase in anthropogenic CO<sub>2</sub> emissions, seems to us to be irrational.

In one final paper from the same year, Lin (2007) states that "a good simulation of tropical mean climate by the climate models is a *prerequisite* [our italics] for their good simulations/predictions of tropical variabilities and global teleconnections," but that "unfortunately, the tropical mean climate has not been well simulated by the coupled general circulation models (CGCMs) *used for climate predictions and projections* [our italics]," noting that "most of the CGCMs produce a double-intertropical convergence zone (ITCZ) pattern," and acknowledging that "a synthetic view of the double-ITCZ problem is still elusive."

To explore the nature of this problem in greater depth, and to hopefully make some progress in resolving it, Lin analyzed tropical mean climate simulations of the 20-year period 1979-99 provided by 22 Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) CGCMs, together with concurrent Atmospheric Model Intercomparison Project (AMIP) runs from 12 of them.

This work revealed, in Lin's words, that "most of the current state-of-the-art CGCMs have some degree of the double-ITCZ problem, which is characterized by excessive precipitation over much of the Tropics (e.g., Northern Hemisphere ITCZ, Southern Hemisphere SPCZ [South Pacific Convergence Zone], Maritime Continent, and equatorial Indian Ocean), and often associated with insufficient precipitation over the equatorial Pacific," as well as "overly strong trade winds, excessive LHF [latent heat flux], and insufficient SWF [shortwave flux], leading to significant cold SST (sea surface temperature) bias in much of the tropical oceans," while additionally noting that "most of the models also simulate insufficient latitudinal asymmetry in precipitation and SST over the eastern Pacific and Atlantic Oceans," *further* stating that "the AMIP runs also produce excessive precipitation over much of the Tropics including the equatorial Pacific, which also leads to overly strong trade winds, excessive LHF, and insufficient SWF," which suggests that "the excessive tropical precipitation is an intrinsic error of the atmospheric models." And if that is not enough, Lin adds that "over the eastern Pacific stratus region, most of the models produce insufficient stratus-SST feedback associated with insufficient sensitivity of stratus cloud amount to SST."

With the solutions to *all* of these long-standing problems continuing to remain "elusive," and with Lin suggesting that the sought-for solutions are in fact *prerequisites* for "good simulations/predictions" of future climate, there is significant reason to conclude that current state-of-the-art CGCM predictions of CO<sub>2</sub>-induced global warming ought not be considered all that reliable.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/p/precipmodelinadeq.php>.

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## 2. FEEDBACK FACTORS

As reported in the Technical Support Document to the ANPR, the sensitivity of earth's climate system to a doubling of pre-industrial CO<sub>2</sub> is somewhere in the range of 1.5 to 4.5°C, with a most likely value of 3°C. However numerous scientific studies suggest this model-derived sensitivity is far too large and that feedbacks in the climate system reduce it to values that are an *order of magnitude* smaller. In this next chapter, we review some of those feedbacks predominately mentioned in the literature, some of which have the ability to *totally offset* the radiative forcing expected from the rise in atmospheric CO<sub>2</sub>.

Additional information on this topic, including reviews of feedback factors not discussed here, can be found at [http://www.co2science.org/subject/f/subject\\_f.php](http://www.co2science.org/subject/f/subject_f.php) under the heading Feedback Factors.

### 2.1. Clouds

Based on data obtained from the Tropical Ocean Global Atmosphere - Coupled Ocean-Atmosphere Response Experiment, Sud *et al.* (1999) demonstrated that deep convection in the tropics acts as a thermostat to keep sea surface temperature (SST) vacillating between approximately 28 and 30°C. Their analysis suggests that as SSTs reach 28-29°C, the cloud-base airmass is charged with the moist static energy needed for clouds to reach the upper troposphere, at which point the cloud cover reduces the amount of solar radiation received at the surface of the sea, while cool and dry downdrafts promote ocean surface cooling by increasing sensible and latent heat fluxes there. This "thermostat-like control," as Sud *et al.* describe it, tends "to ventilate the tropical ocean efficiently and help contain the SST between 28-30°C." The phenomenon would also be expected to prevent SSTs from rising any higher in response to enhanced CO<sub>2</sub>-induced radiative forcing.

Lindzen *et al.* (2001) used upper-level cloudiness data obtained from the Japanese Geostationary Meteorological Satellite and SST data obtained from the National Centers for Environmental Prediction to derive a strong inverse relationship between upper-level cloud area and the mean SST of cloudy regions of the eastern part of the western Pacific (30°S-30°N; 130°E-170°W), such that the area of cirrus cloud coverage normalized by a measure of the area of cumulus coverage decreases about 22% per degree C increase in the SST of the cloudy region. In describing this phenomenon, Lindzen *et al.* say "the cloudy-moist region appears to act as an infrared adaptive iris that opens up and closes down the regions free of upper-level clouds, which more effectively permit infrared cooling, in such a manner as to resist changes in tropical surface temperature." However, Hartmann and Michelsen (2002), in an analysis of spatial patterns of anomalous cloudiness and winds associated with the negative correlation between cloud-weighted SST and high-cloud fraction, claim that the correlation noted by Lindzen *et al.* results from variations in subtropical clouds that are not physically connected to deep convection near the equator, and that it is thus "unreasonable to interpret these changes as evidence that deep tropical convective anvils contract in response to SST increases."

In a contemporaneous study, Fu *et al.* (2002) continued to chip away at the *adaptive infrared iris* concept of Lindzen *et al.*, arguing that "the contribution of tropical high clouds to the feedback process would be small since the radiative forcing over the tropical high cloud region is near zero and not strongly positive." They also claim to show that "the water vapor and low cloud effects are overestimated [by Lindzen *et al.*] by at least 60% and 33%, respectively." As a result, they obtain a feedback factor "in the range of -0.15 to -0.51, compared to [Lindzen *et al.*'s] larger negative feedback factor of -0.45 to -1.03."

A year later, Chou *et al.* (2002) replied that Fu *et al.*'s approach of specifying longwave emission and cloud albedos "appears to be inappropriate for studying the iris effect." Also, they say that from the point of view that "thin cirrus are widespread in the tropics and that low boundary clouds are optically thick, the cloud albedo calculated by [Fu *et al.*] is too large for cirrus clouds and too small for boundary layer clouds," so that "the near-zero contrast in cloud albedos derived by [Fu *et al.*] has the effect of underestimating the iris effect." They ultimately agree that Lindzen *et al.* "may indeed have overestimated the iris effect somewhat, though hardly by as much as that suggested by [Fu *et al.*]."

The debate over the reality and/or magnitude of the *adaptive infrared iris effect* proposed by Lindzen *et al.* as a powerful means for thwarting CO<sub>2</sub>-induced increases in the atmosphere's greenhouse effect continues apace. There has been some convergence in the two extreme views; but the controversy appears likely to continue for yet some time.

In a more straightforward study, Croke *et al.* (1999) used land-based observations of cloud cover for three regions of the United States (coastal southwest, coastal northeast, and southern plains) to demonstrate that, over the period 1900-1987, cloud cover had a high correlation with global air temperature, with mean cloud cover rising from an initial value of 35% to a final value of 47% as the mean global air temperature rose by 0.5°C. This phenomenon would again tend to counteract the effects of any impetus for warming.

In another study, Herman *et al.* (2001) used Total Ozone Mapping Spectrometer 380-nm reflectivity data to determine changes in radiation reflected back to space over the period 1979 to 1992, finding that "when the 11.3-year solar-cycle and ENSO effects are removed from the time series, the zonally averaged annual linear-fit trends show that there have been increases in reflectivity (cloudiness) poleward of 40°N and 30°S, with some smaller but significant changes occurring in the equatorial and lower middle latitudes." The overall long-term effect was an increase in radiation reflected back to space of 2.8 Wm<sup>-2</sup> per decade, which represents a large cloud-induced cooling influence.

Last of all, Rosenfeld (2000) used satellite data obtained from the Tropical Rainfall Measuring Mission to look for terrestrial analogues of the cloud trails that form in the wakes of ships at sea as a consequence of their emissions of particulates that redistribute cloud-water into larger numbers of smaller droplets that do not rain out of the atmosphere as readily as they would in the absence of this phenomenon. Visualizations produced from the mission data clearly

revealed the existence of enhanced cloud trails downwind of urban and industrial complexes in Turkey, Canada and Australia, to which Rosenfeld gave the name *pollution tracks* in view of their similarity to *ship tracks*. Rosenfeld also demonstrated that the clouds comprising these pollution tracks were composed of droplets of reduced size that did indeed suppress precipitation by inhibiting further coalescence and ice precipitation formation. As Toon (2000) noted in a commentary on this study, these smaller droplets will not "rain out" as quickly and will therefore last longer and cover more of the earth, both of which effects tend to cool the globe.

In summation, as the earth warms, the atmosphere has a tendency to become more cloudy and exert a natural brake upon the rising temperature. Also, many of humanity's aerosol-producing activities tend to do the same thing. Hence, there appear to be a number of different ways in which cloud-mediated processes help the planet to "keep its cool," relatively speaking.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/f/feedbackcloud.php>.

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## **2.2. Carbonyl Sulfide**

Some time ago, Idso (1990) suggested that the volatilization of reduced sulfur gases from earth's soils may be just as important as dimethyl sulfide (DMS) emissions from the world's oceans in enhancing cloud albedo and thereby cooling the planet and providing a natural brake on the tendency for anthropogenically-enhanced greenhouse gases to drive global warming (see Dimethyl Sulfide above). On the basis of experiments that showed soil DMS emissions to be positively correlated with soil organic matter content, and noting that additions of organic matter to soils tend to increase the amount of sulfur gases they emit, Idso hypothesized that because atmospheric CO<sub>2</sub> enrichment augments plant growth and, as a result, vegetative inputs of organic matter to earth's soils, this phenomenon should produce an impetus for cooling, even in the absence of the surface warming that sets in motion the chain of events that produce the oceanic DMS-induced negative-feedback that tends to cool the planet.

Two years later, Idso (1992) expanded this concept to include another biologically-produced sulfur gas that is emitted from soils (carbonyl sulfide or OCS), noting that it too is likely to be emitted in increasingly greater quantities as earth's vegetation responds to the aerial fertilization effect of the ongoing rise in the air's CO<sub>2</sub> content, while pointing out that OCS is relatively inert in the troposphere, but that it eventually makes its way into the stratosphere, where it is transformed into solar-radiation-reflecting sulfate aerosol particles. He consequently concluded that the CO<sub>2</sub>-induced augmentation of soil OCS emissions constitutes a mechanism that can cool the planet's surface (1) in the absence of an impetus for warming (2) without producing additional clouds or (3) making them any brighter.

So what have we subsequently learned about the latter of these two natural cooling phenomena, i.e., the one that involves biologically-mediated increases in carbonyl sulfide emissions? One important thing is that the OCS-induced cooling mechanism also operates at sea, just as the DMS-induced cooling mechanism does, and that it too possesses a warming-induced component in addition to its CO<sub>2</sub>-induced component.

In a study contemporary with that of Idso (1992), ocean-surface OCS concentrations were demonstrated by Andreae and Ferek (1992) to be highly correlated with surface-water primary productivity. So strong is this correlation, in fact, that Erickson and Eaton (1993) developed an empirical model for computing ocean-surface OCS concentrations based solely on surface-water chlorophyll concentrations and values of incoming solar radiation. It has also been learned that an even greater portion of naturally-produced OCS is created in the atmosphere, where carbon disulfide and dimethyl sulfide - also largely of oceanic origin (Aydin *et al.*, 2002) - undergo photochemical oxidation (Khalil and Rasmussen, 1984; Barnes *et al.*, 1994). Hence, the majority of the tropospheric burden of OCS is ultimately dependent upon photosynthetic activity occurring near the surface of the world's oceans.

Why is this important? It is important because the tropospheric OCS concentration has risen by approximately 30% since the 1600s, from a mean value of 373 ppt over the period 1616-1694

to something on the order of 485 ppt today. This is a sizeable increase; and Aydin *et al.* (2002) note that only a fourth of it can be attributed to anthropogenic sources. Consequently, the rest of the observed OCS increase must have had a natural origin, a large portion of which must have ultimately been derived from the products and byproducts of marine photosynthetic activity, which must have increased substantially over the last three centuries. What is more, a solid case can be made for the proposition that both the increase in atmospheric CO<sub>2</sub> concentration and the increase in temperature experienced over this period were the driving forces for the concomitant increase in tropospheric OCS concentration and its likely subsequent transport to the stratosphere, where it could exert a cooling influence on the earth and that may have kept the warming of the globe considerably below what it might otherwise have been in the absence of this chain of events.

Another fascinating aspect of this multifaceted global "biothermostat" was revealed in a laboratory study of samples of the lichen *Ramalina menziesii*, which were collected from an open oak woodland in central California, USA, by Kuhn and Kesselmeier (2000). They found that when the lichens were optimally hydrated, they *absorbed* OCS from the air at a rate that gradually doubled as air temperature rose from approximately 3 to 25°C, whereupon their rate of OCS absorption began a precipitous decline that led to zero OCS absorption at 35°C.

The first portion of this response can be explained by the fact that most terrestrial plants prefer much warmer temperatures than a mere 3°C, so that as their surroundings warm and they grow better, they extract more OCS from the atmosphere in an attempt to promote even more warming and grow better still. At the point where warming becomes a detriment to them, however, they reverse this course of action and begin to rapidly *reduce* their rates of OCS absorption in an attempt to forestall warming-induced death. And since the consumption of OCS by lichens is under the physiological control of carbonic anhydrase - which is the key enzyme for OCS uptake in all higher plants, algae and soil organisms - we could expect this phenomenon to be generally operative over most of the earth. Hence, this *thermoregulatory function of the biosphere* may well be powerful enough to define an upper limit above which the surface air temperature of the planet may be restricted from rising, even when changes in other forcing factors, such as increases in greenhouse gas concentrations, produce an impetus for it to do so.

Clearly, this multifaceted phenomenon is extremely complex, with different biological entities tending to both increase and decrease atmospheric OCS concentrations at one and the same time, while periodically reversing directions in this regard in response to climate changes that push the temperatures of their respective environments either above or below the various thermal optima at which they function best. This being the case, there is obviously much more we need to learn about the many plant physiological mechanisms that may be involved. Nevertheless, state-of-the-art climate models *totally neglect* these and many other vital biological processes (some of which may yet be undiscovered) that combine to determine the mean state of earth's climate.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/c/carbonylsulfide.php>.

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### 2.3. Diffuse Light

The initial impetus for the increase in surface air temperature in the negative feedback phenomenon we describe here focuses exclusively on the incremental enhancement of the atmosphere's greenhouse effect that is produced by an increase in the air's CO<sub>2</sub> content; and from this starting point we identify a chain of events that ultimately counteracts this impetus for warming by the incremental enhancement of the planet's natural rate of CO<sub>2</sub> removal from the air.

The first of the linkages in this negative feedback loop is the proven propensity for higher levels of atmospheric CO<sub>2</sub> to enhance vegetative productivity, which phenomena are themselves powerful negative feedback mechanisms of the type we envision. Greater CO<sub>2</sub>-enhanced photosynthetic rates, for example, enable plants to remove considerably more CO<sub>2</sub> from the air than they do under current conditions; while CO<sub>2</sub>-induced increases in plant water use efficiency allow plants to grow where it was previously too dry for them. This latter



consequence of atmospheric CO<sub>2</sub> enrichment establishes a potential for more CO<sub>2</sub> to be removed from the atmosphere by increasing the *abundance* of earth's plants, whereas the former phenomenon does so by increasing their *robustness*.

The second of the linkages of the new feedback loop is the ability of plants to emit gases to the atmosphere that are ultimately converted into "biosols," i.e., aerosols that owe their existence to the biological activities of earth's vegetation, many of which function as cloud condensation nuclei. It takes little imagination to realize that since the existence of these atmospheric particles is dependent upon the physiological activities of plants and their associated soil biota, the CO<sub>2</sub>-induced presence of more and more-highly-productive plants will lead to the production of more of these cloud-mediating particles, which can then act to cool the planet. But this two-linkage-long negative feedback effect, like the one-linkage-long dual cooling mechanism described in the previous paragraph, is still not the endpoint of the new feedback loop we are describing.

The third linkage of the new scenario is the observed propensity for increases in aerosols and cloud particles to enhance the amount of diffuse solar radiation reaching the earth's surface. The fourth linkage is the ability of enhanced diffuse lighting to reduce the volume of shade within vegetative canopies. The fifth linkage is the tendency for less internal canopy shading to enhance whole-canopy photosynthesis, which finally produces the end result: a greater biological extraction of CO<sub>2</sub> from the air and the subsequent sequestration of its carbon, compliments of the intensified diffuse-light-driven increase in total canopy photosynthesis and subsequent transfers of the extra fixed carbon to plant and soil storage reservoirs.

How significant is this multi-link process? Roderick *et al.* (2001) provide a good estimate based on the utilization of a unique "natural experiment," a technique that has been used extensively by Idso (1998) to evaluate the climatic sensitivity of the entire planet. Specifically, Roderick and his colleagues considered the volcanic eruption of Mt. Pinatubo in June of 1991, which ejected enough gases and fine materials into the atmosphere to produce sufficient aerosol particles to greatly increase the diffuse component of the solar radiation reaching the surface of the earth from that point in time through much of 1993, while only slightly reducing the receipt of total solar radiation. Based on a set of lengthy calculations, they concluded that the Mt. Pinatubo eruption may well have resulted in the removal of an extra 2.5 Gt of carbon from the atmosphere due to its diffuse-light-enhancing stimulation of terrestrial vegetation in the year following the eruption, which would have reduced the ongoing rise in the air's CO<sub>2</sub> concentration that year by about 1.2 ppm.

Interestingly, this reduction is about the magnitude of the real-world perturbation that was actually observed (Sarmiento, 1993). What makes this observation even more impressive is the fact that the CO<sub>2</sub> reduction was coincident with an El Niño event; because, in the words of Roderick *et al.*, "previous and subsequent such events have been associated with *increases* in atmospheric CO<sub>2</sub>." In addition, the observed reduction in total solar radiation received at the earth's surface during this period would have had a tendency to reduce the amount of photosynthetically active radiation incident upon earth's plants, which would also have had a

tendency to cause the air's CO<sub>2</sub> content to rise, as it would tend to lessen global photosynthetic activity.

Significant support for the new negative feedback phenomenon was swift in coming, as the very next year a team of 33 researchers published the results of a comprehensive study (Law *et al.*, 2002) that compared seasonal and annual values of CO<sub>2</sub> and water vapor exchange across sites in forests, grasslands, crops and tundra -- which are part of an international network called FLUXNET -- investigating the responses of these exchanges to variations in a number of environmental factors, including direct and diffuse solar radiation. As for their findings, the huge group of researchers reported that "net carbon uptake (net ecosystem exchange, the net of photosynthesis and respiration) was greater under diffuse than under direct radiation conditions," and in discussing this finding, which is the centerpiece of the negative feedback phenomenon we describe, they noted that "cloud-cover results in a greater proportion of diffuse radiation and constitutes a higher fraction of light penetrating to lower depths of the canopy (Oechel and Lawrence, 1985)." More importantly, they also reported that "Goulden *et al.* (1997), Fitzjarrald *et al.* (1995), and Sakai *et al.* (1996) showed that net carbon uptake was consistently higher during cloudy periods in a boreal coniferous forest than during sunny periods with the same PPFD [photosynthetic photon flux density]." In fact, they wrote that "Hollinger *et al.* (1994) found that daily net CO<sub>2</sub> uptake was greater on cloudy days, *even though total PPFD was 21-45% lower on cloudy days than on clear days* [our italics]."

One year later, Gu *et al.* (2003) reported that they "used two independent and direct methods to examine the photosynthetic response of a northern hardwood forest (Harvard Forest, 42.5°N, 72.2°W) to changes in diffuse radiation caused by Mount Pinatubo's volcanic aerosols," finding that in the eruption year of 1991, "around noontime in the mid-growing season, the gross photosynthetic rate under the perturbed *cloudless* [our italics] solar radiation regime was 23, 8, and 4% higher than that under the normal *cloudless* [our italics] solar radiation regime in 1992, 1993, and 1994, respectively," and that "integrated over a day, the enhancement for canopy gross photosynthesis by the volcanic *aerosols* [our italics] was 21% in 1992, 6% in 1993 and 3% in 1994." Commenting on the significance of these observations, Gu *et al.* noted that "because of substantial increases in diffuse radiation world-wide after the eruption and strong positive effects of diffuse radiation for a variety of vegetation types, it is likely that our findings at Harvard Forest represent a *global* [our italics] phenomenon."

In the preceding paragraph, we have highlighted the fact that the diffuse-light-induced photosynthetic enhancement observed by Gu *et al.*, in addition to likely being global in scope, was caused by volcanic *aerosols* under acting under *cloudless* conditions. Our reason for calling attention to these two italicized words is to clearly distinguish this phenomenon from a closely related one that is also described by Gu *et al.*, i.e., the propensity for the extra diffuse light created by *increased cloud cover* to further enhance photosynthesis, *even though the total flux of solar radiation received at the earth's surface may be reduced under such conditions*. Based on still more real-world data, for example, Gu *et al.* note that "Harvard Forest photosynthesis also increases with cloud cover, with a peak at about 50% cloud cover."

Although very impressive, in all of the situations discussed above the source of the enhanced atmospheric aerosol concentration was a singular significant event -- specifically, a massive volcanic eruption -- but what we really need to know is what happens under more normal conditions. This was the new and important question that was addressed the following year in the study of Niyogi *et al.* (2004): "Can we detect the effect of relatively routine aerosol variability on field measurements of CO<sub>2</sub> fluxes, and if so, how does the variability in aerosol loading affect CO<sub>2</sub> fluxes over different landscapes?"

To answer this question, the group of sixteen researchers used CO<sub>2</sub> flux data from the AmeriFlux network (Baldocchi *et al.*, 2001) together with cloud-free aerosol optical depth data from the NASA Robotic Network (AERONET; Holben *et al.*, 2001) to assess the effect of aerosol loading on the net assimilation of CO<sub>2</sub> by three types of vegetation: trees (broadleaf deciduous forest and mixed forest), crops (winter wheat, soybeans and corn) and grasslands. Their work revealed that an aerosol-induced increase in *diffuse radiative-flux fraction* [DRF = ratio of diffuse (R<sub>d</sub>) to total or global (R<sub>g</sub>) solar irradiance] increased the net CO<sub>2</sub> assimilation of trees and crops, making them larger carbon sinks, but that it decreased the net CO<sub>2</sub> assimilation of grasslands, making them smaller carbon sinks.

How significant were the effects observed by Niyogi *et al.*? For a summer mid-range R<sub>g</sub> flux of 500 W m<sup>-2</sup>, going from the set of all DRF values between 0.0 and 0.4 to the set of all DRF values between 0.6 and 1.0 resulted in an approximate 50% increase in net CO<sub>2</sub> assimilation by a broadleaf deciduous forest located in Tennessee, USA. Averaged over the entire daylight period, they further determined that the shift from the lower to the higher set of DRF values "enhances photosynthetic fluxes by about 30% at this study site." Similar results were obtained for the mixed forest and the conglomerate of crops studied. Hence, they concluded that natural variability among commonly-present aerosols can "routinely influence surface irradiance and hence the terrestrial CO<sub>2</sub> flux and regional carbon cycle." And for these types of land-cover (forests and agricultural crops), that influence is to significantly *increase* the assimilation of CO<sub>2</sub> from the atmosphere.

In the case of grasslands, however, the effect was found to be just the opposite, with greater aerosol loading of the atmosphere leading to *less* CO<sub>2</sub> assimilation, due most likely, in the estimation of Niyogi *et al.*, to grasslands' significantly different canopy architecture. With respect to the planet as a whole, however, the net effect is decidedly positive, as earth's trees are the primary planetary players in the sequestration of carbon. Post *et al.* (1990), for example, noted that woody plants account for approximately 75% of terrestrial photosynthesis, which comprises about 90% of the global total (Sellers and McCarthy, 1990); and those numbers make earth's trees and shrubs responsible for fully two thirds (0.75 x 90% = 67.5%) of the planet's net primary production.

What is especially exciting about these real-world observations is that much of the commonly-present aerosol burden of the atmosphere is plant-derived. Hence, it can be appreciated that earth's woody plants are themselves responsible for emitting to the air that which ultimately enhances their own photosynthetic prowess. In other words, earth's trees significantly control

their own destiny, i.e., they alter the atmospheric environment in a way that directly enhances their opportunities for greater growth.

Society helps too, in this regard; for as we pump ever more CO<sub>2</sub> into the atmosphere, the globe's woody plants quickly respond to its *aerial fertilization effect*, becoming ever more productive, which leads to even more plant-derived aerosols being released to the atmosphere, which stimulates this positive feedback cycle to a still greater degree. Stated another way, earth's trees use some of the CO<sub>2</sub> emitted to the atmosphere by society to alter the aerial environment so as to enable them to remove even more CO<sub>2</sub> from the air. The end result is that earth's trees and humanity are working *hand-in-hand* to significantly increase the productivity of the biosphere; and it is happening in spite of all other insults to the environment that work in opposition to enhanced biological activity.

In light of these several observations, it should be obvious that the historical and still-ongoing CO<sub>2</sub>-induced increase in atmospheric *biosols* should have had, and should be continuing to have, a significant cooling effect on the planet that exerts itself by both slowing the rate of rise of the air's CO<sub>2</sub> content and reducing the receipt of solar radiation at the earth's surface, neither of which effects is fully and adequately included in any general circulation model of the atmosphere of which we are aware.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/f/feedbackdiffuse.php>.

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## 2.4. Iodocompounds

The climatic significance of iodinated compounds or *iodocompounds* was first described in the pages of *Nature* by O'Dowd *et al.* (2002). As related by Kolb (2002) in an accompanying perspective on their work, the ten-member research team discovered "a previously unrecognized source of aerosol particles" by unraveling "a photochemical phenomenon that occurs in sea air and produces aerosol particles composed largely of iodine oxides." Specifically, the team used a smog chamber operated under coastal atmospheric conditions to demonstrate, as they report, that "new particles can form from condensable iodine-containing vapors, which are the photolysis products of biogenic iodocarbons emitted from marine algae." With the help of aerosol formation models, they also demonstrated that concentrations of condensable iodine-containing vapors over the open ocean "are sufficient to influence marine particle formation."

The significance of this work, of course, is that the aerosol particles O'Dowd *et al.* discovered can function as cloud condensation nuclei (CCN), helping to create new clouds that reflect more incoming solar radiation back to space and thereby cool the planet. With respect to the negative feedback nature of this phenomenon, O'Dowd *et al.* cite the work of Laturnus *et al.* (2000), which demonstrates that emissions of iodocarbons from marine biota "can increase by up to 5 times as a result of changes in environmental conditions associated with global change." Therefore, as O'Dowd *et al.* continue, "increasing the source rate of condensable iodine vapors will result in an increase in marine aerosol and CCN concentrations of the order of 20 - 60%." Furthermore, they note that "changes in cloud albedo resulting from changes in CCN concentrations of this magnitude can lead to an increase in global radiative forcing *similar in magnitude, but opposite in sign* [our italics], to the forcing induced by greenhouse gases."

Four years later, Smythe-Wright *et al.* (2006) measured trace gas and pigment concentrations in seawater, while identifying and enumerating picophytoprokaroyotes during two ship cruises in the Atlantic Ocean and one in the Indian Ocean, where they focused "on methyl iodide production and the importance of a biologically related source." In doing so, they encountered methyl iodide concentrations as great as 45 pmol per liter in the top 150 meters of the oceanic water column that correlated well with the abundance of *Prochlorococcus*, which they report "can account for >80% of the variability in the methyl iodide concentrations," they add that they "have confirmed the release of methyl iodide by this species in laboratory culture experiments."

Extrapolating their findings to the globe as a whole, the six researchers "estimate the global ocean flux of iodine [I] to the marine boundary layer from this single source to be  $5.3 \times 10^{11}$  g I year<sup>-1</sup>," which they say "is a large fraction of the total estimated global flux of iodine ( $10^{11}$ - $10^{12}$  g I year<sup>-1</sup>)." This observation is extremely important, because volatile iodinated compounds, in Smythe-Wright *et al.*'s words, "play a part in the formation of new particles and cloud condensation nuclei (CCN)," and because "an increase in the production of iodocompounds and the subsequent production of CCN would potentially result in a net cooling of the earth system"

and hence in a negative climate feedback mechanism, mitigating global warming." More specifically, they suggest that "as ocean waters become warmer and more stratified, nutrient concentrations will fall and there will likely be a regime shift away from microalgae toward *Prochlorococcus*," such that "colonization within the <50° latitude band will result in a ~15% increase in the release of iodine to the atmosphere," with consequent "important implications for global climate change," which, as previously noted, tend to counteract global warming.

Most recently, as part of the Third Pelagic Ecosystem CO<sub>2</sub> Enrichment Study, Wingenter *et al.* (2007) investigated the effects of atmospheric CO<sub>2</sub> enrichment on marine microorganisms in nine marine mesocosms maintained within two-meter-diameter polyethylene bags submerged to a depth of ten meters in a fjord at the Large-Scale Facilities of the Biological Station of the University of Bergen in Espegrend, Norway. Three of these mesocosms were maintained at ambient levels of CO<sub>2</sub> (~375 ppm or base CO<sub>2</sub>), three were maintained at levels expected to prevail at the end of the current century (760 ppm or 2xCO<sub>2</sub>), and three were maintained at levels predicted for the middle of the next century (1150 ppm or 3xCO<sub>2</sub>). During the 25 days of this experiment, the twelve researchers followed the development and subsequent decline of an induced bloom of the coccolithophorid *Emiliania huxleyi*, carefully measuring several physical, chemical and biological parameters along the way. This work revealed that the iodocarbon chloriodomethane (CH<sub>2</sub>CI) experienced its peak concentration about six to ten days after the coccolithophorid's chlorophyll-a maximum, and that its estimated abundance was 46% higher in the 2xCO<sub>2</sub> mesocosms and 131% higher in the 3xCO<sub>2</sub> mesocosms.

The international team of scientists concluded that the differences in the CH<sub>2</sub>CI concentrations "may be viewed as a result of changes to the ecosystems as a whole brought on by the CO<sub>2</sub> perturbations." And because emissions of various iodocarbons have been found to lead to an enhancement of cloud condensation nuclei in the marine atmosphere, as demonstrated by O'Dowd *et al.* (2002) and Jimenez *et al.* (2003), it can be appreciated that the CO<sub>2</sub>-induced stimulation of the marine emissions of these substances provides a *natural brake* on the tendency for global warming to occur as a consequence of *any* forcing, as iodocarbons lead to the creation of more-highly-reflective clouds over greater areas of the world's oceans.

In conclusion, as Wingenter *et al.* sum things up, the processes described above "may help contribute to the homeostasis of the planet." And the finding of O'Dowd *et al.* that changes in cloud albedo "associated with global change" can lead to an increase in global radiative forcing that is "similar in magnitude, but opposite in sign, to the forcing induced by greenhouse gases," suggests that CO<sub>2</sub>-induced increases in marine iodocarbon emissions likely contribute to maintaining that homeostasis in a really big way.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/f/feedbackiodo.php>.

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## **2.5. Nitrous Oxide**

One of the main sources of N<sub>2</sub>O is *agriculture*, which in some countries accounts for almost half of a nations' N<sub>2</sub>O emissions (Pipatti, 1997). Moreover, with N<sub>2</sub>O originating from microbial N cycling in soil -- mostly from aerobic nitrification or from anaerobic denitrification (Firestone and Davidson, 1989) -- there is a concern that CO<sub>2</sub>-induced increases in carbon input to soil, together with increasing N input from other sources, will increase substrate availability for denitrifying bacteria and may result in higher N<sub>2</sub>O emissions from agricultural soils as the air's CO<sub>2</sub> content continues to rise.

In a study designed to investigate this possibility, Kettunen *et al.* (2007a) grew mixed stands of timothy (*Phleum pratense*) and red clover (*Trifolium pratense*) in sandy-loam-filled mesocosms at low and moderate soil nitrogen levels within greenhouses maintained at either 360 or 720 ppm CO<sub>2</sub>, while measuring harvestable biomass production and N<sub>2</sub>O evolution from the mesocosm soils over the course of three crop cuttings. This work revealed that the total harvestable biomass production of *P. pratense* was enhanced by the experimental doubling of the air's CO<sub>2</sub> concentration by 21 and 26%, respectively, in the low and moderate soil N treatments, while corresponding biomass enhancements for *T. pratense* were 22 and 18%. In addition, the researchers found that after emergence of the mixed stand and during vegetative growth before the first harvest and N fertilization, N<sub>2</sub>O fluxes were higher under *ambient* CO<sub>2</sub> in both the low and moderate soil N treatments. In fact, it was not until the water table had been raised and extra fertilization given after the first harvest that the elevated CO<sub>2</sub> seemed to increase N<sub>2</sub>O fluxes. The four Finnish researchers thus concluded that the mixed stand of *P.*



*pratense* and *T. pratense* was "able to utilize the increased supply of atmospheric CO<sub>2</sub> for enhanced biomass production without a simultaneous increase in the N<sub>2</sub>O fluxes," thereby raising "the possibility of maintaining N<sub>2</sub>O emissions at their current level, while still enhancing the yield production [via the *aerial fertilization effect* of elevated CO<sub>2</sub>] even under low N fertilizer additions."

In a similar study, Kettunen *et al.* (2007b) grew timothy (*Phleum pratense*) in monoculture within sandy-soil-filled mesocosms located within greenhouses maintained at atmospheric CO<sub>2</sub> concentrations of either 360 or 720 ppm for a period of 3.5 months at *moderate* (standard), *low* (half-standard) and *high* (1.5 times standard) soil N supply, while they measured the evolution of N<sub>2</sub>O from the mesocosms, vegetative net CO<sub>2</sub> exchange, and final above- and below-ground biomass production over the course of three harvests. In this experiment the elevated CO<sub>2</sub> concentration increased the net CO<sub>2</sub> exchange of the ecosystems (which phenomenon was primarily driven by CO<sub>2</sub>-induced increases in photosynthesis) by about 30%, 46% and 34% at the low, moderate and high soil N levels, respectively, while it increased the above-ground biomass of the crop by about 8%, 14% and 8% at the low, moderate and high soil N levels, and its below-ground biomass by 28%, 27% and 41% at the same respective soil N levels. And once again, Kettunen *et al.* report that "an explicit increase in N<sub>2</sub>O fluxes due to the elevated atmospheric CO<sub>2</sub> concentration was not found."

One year later, Welzmilller *et al.* measured N<sub>2</sub>O and denitrification emission rates in a C<sub>4</sub> sorghum [*Sorghum bicolor* (L.) Moench] production system with ample and limited flood irrigation rates under Free-Air CO<sub>2</sub> Enrichment (seasonal mean = 579 ppm) and control (seasonal mean = 396 ppm) CO<sub>2</sub> during the 1998 and 1999 summer growing seasons at the experimental FACE site near Maricopa, Arizona (USA). Results of the study indicated that "elevated CO<sub>2</sub> did not result in increased N<sub>2</sub>O or N-gas emissions with either ample or limited irrigation," which findings they describe as being "consistent with findings for unirrigated western U.S. ecosystems reported by Billings *et al.* (2002) for Mojave Desert soils and by Mosier *et al.* (2002) for Colorado shortgrass steppe."

In discussing the implications of their findings, Welzmilller *et al.* say their results suggest that "as CO<sub>2</sub> concentrations increase, there will not be major increases in denitrification in C<sub>4</sub> cropping environments such as irrigated sorghum in the desert southwestern United States," which further suggests there will not be an increased impetus for global warming due to this phenomenon.

In a different type of study -- driven by the possibility that the climate of the Amazon Basin may gradually become drier due to a warming-induced increase in the frequency and/or intensity of El Niño events that have historically brought severe drought to the region -- Davidson *et al.* (2004) devised an experiment to determine the consequences of the drying of the soil of an Amazonian moist tropical forest for the net surface-to-air fluxes of both N<sub>2</sub>O and methane (CH<sub>4</sub>). This they did in the Tapajos National Forest near Santarem, Brazil, by modifying a one-hectare plot of land covered by mature evergreen trees so as to dramatically reduce the

amount of rain that reached the forest floor (throughfall), while maintaining an otherwise similar one-hectare plot of land as a control for comparison.

Prior to making this modification, the three researchers measured the gas exchange characteristics of the two plots for a period of 18 months; then, after initiating the throughfall-exclusion treatment, they continued their measurements for an additional three years. This work revealed that the "drier soil conditions caused by throughfall exclusion inhibited N<sub>2</sub>O and CH<sub>4</sub> production and promoted CH<sub>4</sub> consumption." In fact, they report that "the exclusion manipulation lowered annual N<sub>2</sub>O emissions by >40% and increased rates of consumption of atmospheric CH<sub>4</sub> by a factor of >4," which results they attributed to the "direct effect of soil aeration on denitrification, methanogenesis, and methanotrophy."

Consequently, if global warming would indeed increase the frequency and/or intensity of El Niño events as some claim it will, the results of this study suggest that the anticipated drying of the Amazon Basin would initiate a strong *negative* feedback via (1) large drying-induced reductions in the evolution of both N<sub>2</sub>O and CH<sub>4</sub> from its soils, and (2) a huge drying-induced increase in the consumption of CH<sub>4</sub> by its soils. Although Davidson et al. envisage a more extreme *second phase response* "in which drought-induced plant mortality is followed by increased mineralization of C and N substrates from dead fine roots and by increased foraging of termites on dead coarse roots" (an extreme response that would be expected to *increase* N<sub>2</sub>O and CH<sub>4</sub> emissions), we note that the projected rise in the air's CO<sub>2</sub> content would likely prohibit such a thing from ever occurring, due to the documented tendency for atmospheric CO<sub>2</sub> enrichment to greatly increase the water use efficiency of essentially all plants, which would enable the forest to continue to flourish under significantly drier conditions than those of the present.

In summation, it would appear that concerns about additional global warming arising from enhanced N<sub>2</sub>O emissions from agricultural soils in a CO<sub>2</sub>-enriched atmosphere of the future are not well founded.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/n/nitrousoxide.php>.

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## **2.6. Methane**

What impact do global warming, the ongoing rise in the air's carbon dioxide (CO<sub>2</sub>) content and a number of other contemporary environmental trends have on the atmosphere's methane (CH<sub>4</sub>) concentration? The implications of this question are huge, in light of the fact that methane is a more powerful greenhouse gas, molecule for molecule, than is carbon dioxide. Its atmospheric concentration is determined by the difference between how much CH<sub>4</sub> goes into the air (emissions) and how much comes out of it (extractions) over the same time period. And as indicated in the literature below, there are significant forces at play that will likely produce a large negative feedback toward the future warming potential of this powerful greenhouse gas, nearly all of which forces are not presently included in model projections of future climate. We begin with a discussion of methane emissions associated with agricultural operations.

Early indications that atmospheric CO<sub>2</sub> enrichment might significantly reduce methane emissions associated with the production of rice were provided by Schrope *et al.* (1999), who studied batches of rice growing in large vats filled with topsoil and placed within greenhouse tunnels maintained at atmospheric CO<sub>2</sub> concentrations of 350 and 700 ppm, each of which tunnels was further subdivided into four sections that provided temperature treatments ranging from ambient to as much as 5°C above ambient. As would be expected, doubling the air's CO<sub>2</sub> content significantly enhanced rice biomass production in this system, increasing it by up to 35% above-ground and by up to 83% below-ground. However, in a truly unanticipated development, methane emissions from the rice grown at 700 ppm CO<sub>2</sub> were found to be 10 to 45 times less than emissions from the plants grown at 350 ppm. As Schrope *et al.* describe it, "the results of this study did not support our hypothesis that an effect of both increased carbon

dioxide and temperature would be an increase in methane emissions." Indeed, they report that "both increased carbon dioxide and increased temperatures were observed to produce decreased methane emissions," except for the first 2°C increase above ambient, which produced a slight increase in methane evolution from the plant-soil system.

In checking for potential problems with their experiment, Schrope *et al.* could find none. They thus stated that their results "unequivocally support the conclusion that, during this study, methane emissions from *Oryza sativa* [rice] plants grown under conditions of elevated CO<sub>2</sub> were dramatically reduced relative to plants grown in comparable conditions under ambient levels of CO<sub>2</sub>," and to be doubly sure of this fact, they went on to replicate their experiment in a second year of sampling and obtained essentially the same results. Four years later, however, a study of the same phenomenon by a different set of scientists yielded a far different result in a different set of circumstances.

Inubushi *et al.* (2003) grew a different cultivar of rice in 1999 and 2000 in paddy culture at Shizukuishi, Iwate, Japan in a FACE study where the air's CO<sub>2</sub> concentration was increased 200 ppm above ambient. They found that the extra CO<sub>2</sub> "significantly increased the CH<sub>4</sub> [methane] emissions by 38% in 1999 and 51% in 2000," which phenomenon they attributed to "accelerated CH<sub>4</sub> production as a result of increased root exudates and root autolysis products and to the increased plant-mediated CH<sub>4</sub> emission because of the higher rice tiller numbers under FACE conditions." With such a dramatically different result from that of Schrope *et al.*, many more studies likely will be required to clarify this issue and determine which of these two contrasting results is the more typical of rice culture around the world.

A somewhat related study was conducted by Kruger and Frenzel (2003), who note that "rice paddies contribute approximately 10-13% to the global CH<sub>4</sub> emission (Neue, 1997; Crutzen and Lelieveld, 2001)," and that "during the next 30 years rice production has to be increased by at least 60% to meet the demands of the growing human population (Cassman *et al.*, 1998)." Because of these facts they further note that "increasing amounts of fertilizer will have to be applied to maximize yields [and] there is ongoing discussion on the possible effects of fertilization on CH<sub>4</sub> emissions."

To help promote that discussion, Kruger and Frenzel investigated the effects of N-fertiliser (urea) on CH<sub>4</sub> emission, production and oxidation in rice culture in laboratory, microcosm and field experiments they conducted at the Italian Rice Research Institute in northern Italy. They report that in some prior studies "N-fertilisation stimulated CH<sub>4</sub> emissions (Cicerone and Shetter, 1981; Banik *et al.*, 1996; Singh *et al.*, 1996)," while "methanogenesis and CH<sub>4</sub> emission was found to be inhibited in others (Cai *et al.*, 1997; Schutz *et al.*, 1989; Lindau *et al.*, 1990)," similar to the polarized findings of Schrope *et al.* and Inubushi *et al.* with respect to the effects of elevated CO<sub>2</sub> on methane emissions. In the mean, therefore, there may well be little to no change in overall CH<sub>4</sub> emissions from rice fields in response to both elevated CO<sub>2</sub> and increased N-fertilization. With respect to their own study, for example, Kruger and Frenzel say that "combining our field, microcosm and laboratory experiments we conclude that any agricultural praxis improving the N-supply to the rice plants will also be favourable for the CH<sub>4</sub> oxidising

bacteria," noting that "N-fertilisation had only a transient influence and was counter-balanced in the field by an elevated CH<sub>4</sub> production." The implication of these findings is well articulated in the concluding sentence of their paper: "neither positive nor negative consequences for the overall global warming potential could be found."

Another agricultural source of methane is the fermentation of feed in the rumen of cattle and sheep. Fievez *et al.* (2003) studied the effects of various types and levels of fish-oil feed additives on this process by means of both *in vitro* and *in vivo* experiments with sheep, observing a maximal 80% decline in the ruminants' production of methane when using fish-oil additives containing n-3-eicosapentanoic acid. With respect to cattle, Boadi *et al.* (2004) report that existing mitigation strategies for reducing CH<sub>4</sub> emissions from dairy cows include the addition of ionophores and fats to their food, as well as the use of high-quality forages and grains in their diet, while newer mitigation strategies include "the addition of probiotics, acetogens, bacteriocins, archaeal viruses, organic acids, [and] plant extracts (e.g., essential oils) to the diet, as well as immunization, and genetic selection of cows." To this end, they provide a table of 20 such strategies, where the average *maximum potential* CH<sub>4</sub> reduction that may result from the implementation of *each* strategy is 30% or more.

With as many as 20 different mitigation strategies from which to choose, each one of which (on average) has the potential to reduce CH<sub>4</sub> emissions from dairy cows by as much as a third, it would appear there is a tremendous potential to dramatically curtail the amount of CH<sub>4</sub> released to the atmosphere by these ruminants and, by implication, the host of other ruminants that mankind raises and uses for various purposes around the world. Such high-efficiency approaches to reducing the strength of the atmosphere's greenhouse effect, while not reducing the biological benefits of elevated atmospheric CO<sub>2</sub> concentrations in the process, should be at the top of any program designed to achieve that difficult (but still highly questionable) objective.

In view of these several observations, we can be cautiously optimistic about our agricultural intervention capabilities and their capacity to help stem the tide of earth's historically-rising atmospheric methane concentration, which could take a huge bite out of methane-induced global warming. But what about methane emissions from natural vegetation, do they respond in a similar way?

With respect to methane emissions associated with natural vegetation, we have already discussed the results of Davidson *et al.* (2004) in our *Nitrous Oxide* section, which results suggest that a global warming-induced drying of the Amazon Basin would initiate a strong negative feedback to warming via (1) large drying-induced reductions in the evolution of N<sub>2</sub>O and CH<sub>4</sub> from its soils and (2) a huge drying-induced increase in the consumption of CH<sub>4</sub> by its soils. In a contemporaneous study, Strack *et al.* (2004) also reported that climate models predict increases in evapotranspiration that could lead to drying in a warming world and a subsequent lowering of water tables in high northern latitudes. This prediction literally cries out for an analysis of how lowered water tables will impact peatland emissions of CH<sub>4</sub>; and in a *theoretical* study of the subject, Roulet *et al.* (1992) calculated that for a decline of 14 cm in the

water tables of northern Canadian peatlands, due to climate-model-derived increases in temperature (3°C) and precipitation (1mm/day) predicted for a doubling of the air's CO<sub>2</sub> content, CH<sub>4</sub> emissions would decline by 74-81%. Hence, in an attempt to obtain some *experimental* data on the subject, at various times over the period 2001-2003 Strack *et al.* measured CH<sub>4</sub> fluxes to the atmosphere at different locations that varied in depth-to-water table within natural portions of a poor fen in central Quebec, Canada, as well as within control portions of the fen that had been drained eight years earlier.

At the conclusion of their study, the Canadian scientists reported that "methane emissions and storage were lower in the drained fen." The greatest reductions (up to 97%) were measured at the higher locations, while at the lower locations there was little change in CH<sub>4</sub> flux. Averaged over all locations, they determined that the "growing season CH<sub>4</sub> emissions at the drained site were 55% lower than the control site," indicative of the fact that the biosphere appears to be organized to resist warming influences that could push it into a thermal regime that might otherwise prove detrimental to its health.

In another experimental study, Garnet *et al.* (2005) grew seedlings of three emergent aquatic macrophytes (*Orontium aquaticum* L., *Peltandra virginica* L. and *Juncus effusus* L.) plus one coniferous tree (*Taxodium distichum* L.), all of which are native to eastern North America, in a five-to-one mixture of well-fertilized mineral soil and peat moss in pots submerged in water in tubs located within controlled environment chambers for a period of eight weeks. Concomitantly, they measured the amount of CH<sub>4</sub> emitted by the plant foliage, along with net CO<sub>2</sub> assimilation rate and stomatal conductance, which were made to vary by changing the CO<sub>2</sub> concentration of the air surrounding the plants and the density of the photosynthetic photon flux impinging on them.

Methane emissions from the four wetland species increased linearly with increases in both stomatal conductance and net CO<sub>2</sub> assimilation rate; but the researchers found that changes in stomatal conductance affected foliage methane flux "three times more than equivalent changes in net CO<sub>2</sub> assimilation," making stomatal conductance the more significant of the two CH<sub>4</sub> emission-controllers. In addition, they note that evidence of stomatal control of CH<sub>4</sub> emission has also been reported for *Typha latifolia* (Knapp and Yavitt, 1995) and *Carex* (Morrissey *et al.*, 1993), two other important wetland plants. Hence, since atmospheric CO<sub>2</sub> enrichment leads to approximately equivalent - but oppositely directed - changes in foliar net CO<sub>2</sub> assimilation (which is increased) and stomatal conductance (which is reduced) in most herbaceous plants (which are the type that comprise most wetlands), it can be appreciated that the ongoing rise in the air's CO<sub>2</sub> content should be acting to *reduce* methane emissions from earth's wetland vegetation, because of the three-times-greater negative CH<sub>4</sub> emission impact of the decrease in stomatal conductance compared to the positive CH<sub>4</sub> emission impact of the equivalent increase in net CO<sub>2</sub> assimilation.

In light of the above findings, it would appear that current environmental trends that may impact methane emissions from natural vegetation, including the ongoing rise in the air's CO<sub>2</sub> content, primarily tend to *reduce* this flux; and perhaps that is why the rate-of-rise of the

atmosphere's methane concentration has been steadily declining over the last several years to the point that it is now nearly nil. Still, there are other relevant ways by which methane is also removed from the atmosphere.

According to Prinn *et al.* (1992), one of the major means by which methane is removed from the atmosphere is via oxidation by methanotrophic bacteria in the aerobic zones of soils, the magnitude of which phenomenon is believed to be equivalent to the annual input of methane to the atmosphere (Watson *et al.*, 1992). This soil sink for methane appears to be ubiquitous, as methane uptake has been observed in soils of tundra (Whalen and Reeburgh, 1990), boreal forests (Whalen *et al.*, 1992), temperate forests (Steudler *et al.*, 1989; Yavitt *et al.*, 1990), grasslands (Mosier *et al.*, 1997), arable lands (Jensen and Olsen, 1998), tropical forests (Keller, 1986; Singh *et al.*, 1997), and deserts (Striegl *et al.*, 1992), with forest soils - especially boreal and temperate forest upland soils (Whalen and Reeburgh, 1996) - appearing to be the most efficient in this regard (Le Mer and Roger, 2001).

In an attempt to learn more about this subject, Tamai *et al.* (2003) studied methane uptake rates by the soils of three Japanese cypress plantations composed of 30- to 40-year-old trees. Through all seasons of the year, they found that methane was absorbed by the soils of all three sites, being positively correlated with temperature, as has also been observed in several other studies (Peterjohn *et al.*, 1994; Dobbie and Smith, 1996; Prieme and Christensen, 1997; Saari *et al.*, 1998). Methane absorption was additionally - and even more strongly - positively correlated with the C/N ratio of the cypress plantations' soil organic matter. Based on these results, it can be appreciated that CO<sub>2</sub>-induced global warming, if real, would produce two biologically-mediated negative feedbacks to counter the increase in temperature: (1) a warming-induced increase in methane uptake from the atmosphere that is experienced by essentially all soils, and (2) an increase in soil methane uptake from the atmosphere that is produced by the increase in plant-litter C/N ratio that typically results from atmospheric CO<sub>2</sub> enrichment.

Another study that deals with this topic is that of Menyailo and Hungate (2003), who assessed the influence of six boreal forest species -- spruce, birch, Scots pine, aspen, larch and Arolla pine -- on soil CH<sub>4</sub> consumption in the Siberian artificial afforestation experiment, in which the six common boreal tree species had been grown under common garden conditions for the past 30 years under the watchful eye of the staff of the Laboratory of Soil Science of the Institute of Forest, Siberian Branch of the Russian Academy of Sciences (Menyailo *et al.*, 2002). They determined, in their words, that "soils under hardwood species (aspen and birch) consumed CH<sub>4</sub> at higher rates than soils under coniferous species and grassland." Under low soil moisture conditions, for example, the soils under the two hardwood species consumed 35% more CH<sub>4</sub> than the soils under the four conifers; while under high soil moisture conditions they consumed 65% more. As for the implications of these findings, Pastor and Post (1988) have suggested, in the words of Menyailo and Hungate, that "changes in temperature and precipitation resulting from increasing atmospheric CO<sub>2</sub> concentrations will cause a northward migration of the hardwood-conifer forest border in North America." Consequently, if such a shifting of species does indeed occur, it will likely lead to an increase in methane consumption by soils and a

reduction in methane-induced global warming potential, thereby providing yet another biologically-mediated negative feedback factor that has yet to be incorporated into models of global climate change.

Last of all, we note that increases in the air's CO<sub>2</sub> concentration will likely lead to a net reduction in vegetative isoprene emissions, which, as explained elsewhere in this document under the heading of Isoprene, should also lead to a significant removal of methane from the atmosphere. Hence, as the air's CO<sub>2</sub> content -- and possibly its temperature -- continues to rise, we can expect to see a significant increase in the rate of methane removal from earth's atmosphere, which should help to reduce the potential for further global warming.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/m/methaneextract.php>, <http://www.co2science.org/subject/m/methaneag.php> and <http://www.co2science.org/subject/m/methagnatural.php>.

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## **2.7. Dimethyl Sulfide**

Several years ago, Charlson *et al.* (1987) discussed the plausibility of a multi-stage negative feedback process, whereby warming-induced increases in the emission of dimethyl sulfide

(DMS) from the world's oceans tend to counteract any initial impetus for warming. The basic tenant of their hypothesis was that the global radiation balance is significantly influenced by the albedo of marine stratus clouds (the greater the cloud albedo, the less the input of solar radiation to the earth's surface). The albedo of these clouds, in turn, is known to be a function of cloud droplet concentration (the more and smaller the cloud droplets, the greater the cloud albedo and the reflection of solar radiation), which is dependent upon the availability of cloud condensation nuclei on which the droplets form (the more cloud condensation nuclei, the more and smaller the cloud droplets). And in completing the negative feedback loop, Charlson *et al.* noted that the cloud condensation nuclei concentration often depends upon the flux of biologically-produced DMS from the world's oceans (the higher the sea surface temperature, the greater the sea-to-air flux of DMS).

Since the publication of Charlson *et al.*'s initial hypothesis, much empirical evidence has been gathered in support of its several tenants. One review, for example, states that "major links in the feedback chain proposed by Charlson *et al.* (1987) have a sound physical basis," and that there is "compelling observational evidence to suggest that DMS and its atmospheric products participate significantly in processes of climate regulation and reactive atmospheric chemistry in the remote marine boundary layer of the Southern Hemisphere" (Ayers and Gillett, 2000).

But just how strong is the negative feedback phenomenon proposed by Charlson *et al.*? Is it powerful enough to counter the threat of greenhouse gas-induced global warming? According to the findings of Sciare *et al.* (2000), it may well be able to do just that, for in examining ten years of DMS data from Amsterdam Island in the southern Indian Ocean, these researchers found that a sea surface temperature increase of only 1°C was sufficient to increase the atmospheric DMS concentration by as much as 50%. This finding suggests that the degree of warming typically predicted to accompany a doubling of the air's CO<sub>2</sub> content would increase the atmosphere's DMS concentration by a factor of three or more, providing what they call a "very important" negative feedback that could potentially offset the original impetus for warming.

Other research has shown that this same chain of events can be set in motion by means of phenomena not discussed in Charlson *et al.*'s original hypothesis. Simo and Pedros-Alio (1999), for example, discovered that the depth of the surface mixing-layer has a substantial influence on DMS yield in the short term, via a number of photo-induced (and thereby mixing-depth mediated) influences on several complex physiological phenomena, as do longer-term seasonal variations in vertical mixing, via their influence on seasonal planktonic succession scenarios and food-web structure.

More directly supportive of Charlson *et al.*'s hypothesis was the study of Kouvarakis and Mihalopoulos (2002), who measured seasonal variations of gaseous DMS and its oxidation products - non-sea-salt sulfate (nss-SO<sub>4</sub><sup>2-</sup>) and methanesulfonic acid (MSA) - at a remote coastal location in the Eastern Mediterranean Sea from May 1997 through October 1999, as well as the diurnal variation of DMS during two intensive measurement campaigns conducted in September 1997. In the seasonal investigation, DMS concentrations tracked sea surface

temperature (SST) almost perfectly, going from a low of  $0.87 \text{ nmol m}^{-3}$  in the winter to a high of  $3.74 \text{ nmol m}^{-3}$  in the summer. Such was also the case in the diurnal studies: DMS concentrations were lowest when it was coldest (just before sunrise), rose rapidly as it warmed thereafter to about 1100, after which they dipped slightly and then experienced a further rise to the time of maximum temperature at 2000, whereupon a decline in both temperature and DMS concentration set in that continued until just before sunrise. Consequently, because concentrations of DMS and its oxidation products (MSA and  $\text{nss-SO}_4^{2-}$ ) rise dramatically in response to both diurnal and seasonal increases in SST, there is every reason to believe that the same negative feedback phenomenon would operate in the case of the long-term warming that could arise from increasing greenhouse gas concentrations, and that it could substantially mute the climatic impacts of those gases.

Also of note in this regard, Baboukas *et al.* (2002) report the results of nine years of measurements of methanesulfonate (MS-), an exclusive oxidation product of DMS, in *rainwater* at Amsterdam Island. Their data, too, revealed "a well distinguished seasonal variation with higher values in summer, in line with the seasonal variation of its gaseous precursor (DMS)," which, in their words, "further confirms the findings of Sciare *et al.* (2000)." In addition, the MS- anomalies in the rainwater were found to be closely related to SST anomalies; and Baboukas *et al.* say that this observation provides even more support for "the existence of a positive ocean-atmosphere feedback on the biogenic sulfur cycle above the Austral Ocean, one of the most important DMS sources of the world."

In a newer study of this phenomenon, Toole and Siegel (2004) note that it has been shown to operate as described above in the 15% of the world's oceans "consisting primarily of high latitude, continental shelf, and equatorial upwelling regions," where DMS may be accurately predicted as a function of the ratio of the amount of surface chlorophyll derived from satellite observations to the depth of the climatological mixed layer, which they refer to as the "bloom-forced regime." For the other 85% of the world's marine waters, they demonstrate that modeled surface DMS concentrations are independent of chlorophyll and are a function of the mixed layer depth alone, which they call the "stress-forced regime." So how does the warming-induced DMS negative feedback cycle operate in these waters?

For oligotrophic regimes, Toole and Siegel find that "DMS biological production rates are negatively or insignificantly correlated with phytoplankton and bacterial indices for abundance and productivity while more than 82% of the variability is explained by UVR(325) [ultraviolet radiation at 325 nm]." This relationship, in their words, is "consistent with recent laboratory results (e.g., Sunda *et al.*, 2002)," who demonstrated that intracellular DMS concentration and its biological precursors (particulate and dissolved dimethylsulfoniopropionate) "dramatically increase under conditions of acute oxidative stress such as exposure to high levels of UVR," which "are a function of mixed layer depth."

These results -- which Toole and Siegel confirmed via an analysis of the Dacey *et al.* (1998) 1992-1994 organic sulfur time-series that was sampled in concert with the U.S. JGOFS Bermuda Atlantic Time-Series Study (Steinberg *et al.*, 2001) -- suggest, in their words, "the potential of a

global change-DMS-climate feedback." Specifically, they say that "UVR doses will increase as a result of observed decreases in stratospheric ozone and the shoaling of ocean mixed layers as a result of global warming (e.g., Boyd and Doney, 2002)," and that "in response, open-ocean phytoplankton communities should increase their DMS production and ventilation to the atmosphere, increasing cloud condensing nuclei, and potentially playing out a coupled global change-DMS-climate feedback."

This second DMS-induced negative-feedback cycle, which operates over 85% of the world's marine waters and complements the first DMS-induced negative-feedback cycle, which operates over the other 15%, is but another manifestation of the wonderful capacity of earth's biosphere to regulate its affairs in such a way as to maintain climatic conditions over the vast majority of the planet's surface within bounds conducive to the continued existence of life, in all its variety and richness. In addition, it has been suggested that a DMS-induced negative climate feedback phenomenon also operates over the *terrestrial* surface of the globe, where the volatilization of reduced sulfur gases from soils may be just as important as marine DMS emissions in enhancing cloud albedo (Idso, 1990). On the basis of experiments that showed soil DMS emissions to be positively correlated with soil organic matter content, for example, and noting that additions of organic matter to a soil tend to increase the amount of sulfur gases emitted therefrom, Idso (1990) hypothesized that because atmospheric CO<sub>2</sub> is an effective aerial fertilizer, augmenting its atmospheric concentration and thereby increasing vegetative inputs of organic matter to earth's soils should also produce an impetus for cooling, even in the *absence* of surface warming.

Nevertheless, and in spite of the overwhelming empirical evidence for both land- and ocean-based DMS-driven negative feedbacks to global warming, the effects of these processes have not been fully incorporated into today's state-of-the-art climate models. Hence, the warming they predict in response to future anthropogenic CO<sub>2</sub> emissions must be considerably larger than what could actually occur in the real world. In fact, it is very possible these biologically-driven phenomena could totally compensate for the warming influence of all greenhouse gas emissions experienced to date, as well as all those that are anticipated to occur in the future.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/d/dms.php>.

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### 3. AEROSOLS

What role do aerosols play in modulating earth's climate? Citing the IPCC, the EPA's Technical Support Document estimates the net effect of all aerosols is to produce a cooling effect, with a total direct radiative forcing of  $-0.5 \text{ Wm}^{-2}$ , and an additional indirect cloud albedo forcing of  $-0.7 \text{ Wm}^{-2}$ . However, there are numerous studies in the scientific literature that indicate these estimates are far too small. In fact, many indicate the radiative forcing of aerosols may be as large as, or larger than the radiative forcing due to atmospheric  $\text{CO}_2$ .

Consider, for example, the study of Vogelmann *et al.* (2003), who report that "mineral aerosols have complex, highly varied optical properties that, for equal loadings, can cause differences in the surface IR flux between  $7$  and  $25 \text{ Wm}^{-2}$  (Sokolik *et al.*, 1998)," and that "only a few large-scale climate models currently consider aerosol IR effects (e.g., Tegen *et al.*, 1996; Jacobson, 2001) despite their potentially large forcing." In an attempt to persuade climate modelers to rectify this situation, they used high-resolution spectra to obtain the IR radiative forcing at the earth's surface for aerosols encountered in the outflow from northeastern Asia, based on measurements made by the Marine-Atmospheric Emitted Radiance Interferometer from the NOAA Ship *Ronald H. Brown* during the Aerosol Characterization Experiment-Asia. As a result of this work, the five scientists determined that "daytime surface IR forcings are often a few  $\text{Wm}^{-2}$  and can reach almost  $10 \text{ Wm}^{-2}$  for large aerosol loadings." These values, in their words, "are comparable to or larger than the  $1$  to  $2 \text{ Wm}^{-2}$  change in the globally averaged surface IR forcing caused by greenhouse gas increases since pre-industrial times" and "highlight the importance of aerosol IR forcing which should be included in climate model simulations."

In another study that addressed the magnitude of aerosol radiative effects, Chou *et al.* (2002) analyzed aerosol optical properties retrieved from the satellite-mounted Sea-viewing Wide Field-of-view Sensor (SeaWiFS) and used them in conjunction with a radiative transfer model of the planet's atmosphere to calculate the climatic effects of aerosols over earth's major oceans. In general, this effort revealed that "aerosols reduce the annual-mean net downward solar flux by  $5.4 \text{ Wm}^{-2}$  at the top of the atmosphere, and by  $5.9 \text{ Wm}^{-2}$  at the surface." During the large Indonesian fires of September-December 1997, however, the radiative impetus for cooling at the top of the atmosphere was more than  $10 \text{ Wm}^{-2}$ , while it was more than  $25 \text{ Wm}^{-2}$  at the surface of the sea in the vicinity of Indonesia.

These latter results are similar to those obtained earlier by Wild (1999), who used a comprehensive set of collocated surface and satellite observations to calculate the amount of solar radiation absorbed in the atmosphere over equatorial Africa and compared the results with the predictions of three general circulation models of the atmosphere. This work revealed that the climate models did not properly account for spatial and temporal variations in atmospheric aerosol concentrations, leading them to predict regional and seasonal values of solar radiation absorption in the atmosphere with underestimation biases of up to  $30 \text{ Wm}^{-2}$ .



By way of comparison, as noted in the study of Vogelmann *et al.*, the globally averaged surface IR forcing caused by greenhouse gas increases since pre-industrial times is only 1 to 2  $\text{Wm}^{-2}$ . Hence, it can be appreciated that over much of the planet's surface, the radiative cooling influence of atmospheric aerosols (many of which are produced by anthropogenic activities) must prevail, suggesting a probable net anthropogenic-induced climatic signal that must be very close to zero and nowhere near capable of producing what climate alarmists refer to as the *unprecedented* warming of the 20th century. Thus, one might conclude that the air temperature record on which they rely is either grossly in error or that the warming, if real, is due to something other than anthropogenic  $\text{CO}_2$  emissions.

Aerosol uncertainties and the problems they generate also figure prominently in the study of Anderson *et al.* (2003), who note there are two different ways by which the aerosol forcing of climate may be computed. The first of these approaches is that of *forward* calculation, which is based, in their words, on "knowledge of the pertinent aerosol physics and chemistry." The second approach is *inverse* calculation, based on "the total forcing required to match climate model simulations with observed temperature changes."

The first approach, which relies heavily on *first principles*, utilizes known physical and chemical laws and assumes nothing about the outcome of the calculation. The second approach, in considerable contrast, is based on matching *residuals*, where the aerosol forcing is computed from what is required to match the calculated change in temperature with the observed change over some period of time. Consequently, in the words of Anderson *et al.*, "to the extent that climate models rely on the results of inverse calculations, the possibility of circular reasoning arises."

So which approach do climate models typically employ? "Unfortunately," according to Anderson *et al.*, "virtually all climate model studies that have included anthropogenic aerosol forcing as a driver of climate change have used only aerosol forcing values that are consistent with the inverse approach."

How significant is this choice? Anderson *et al.* report that the negative forcing of anthropogenic aerosols derived by forward calculation is "considerably greater" than that derived by inverse calculation, so much so, in fact, that if forward calculation is employed, the results "differ greatly" and "even the sign of the total forcing is in question," which implies that "natural variability (that is, variability not forced by anthropogenic emissions) is much larger than climate models currently indicate." The bottom line, in the words of Anderson *et al.*, is that "inferences about the causes of surface warming over the industrial period and about climate sensitivity may therefore be in error."

Schwartz (2004) also addressed the subject of uncertainty as it applies to the role of aerosols in climate models. Noting that the National Research Council (1979) concluded that "climate sensitivity [to  $\text{CO}_2$  doubling] is likely to be in the range 1.5-4.5°C" and that "remarkably, despite some two decades of intervening work, neither the central value nor the uncertainty range has changed," he opined that this continuing uncertainty "precludes meaningful model evaluation

by comparison with observed global temperature change or empirical determination of climate sensitivity," and that it "raises questions regarding claims of having reproduced observed large-scale changes in surface temperature over the 20th century."

Schwartz thus contends that climate model predictions of CO<sub>2</sub>-induced global warming "are limited at present by uncertainty in radiative forcing of climate change over the industrial period, which is dominated by uncertainty in forcing by aerosols," and that if this situation is not improved, "it is likely that in another 20 years it will still not be possible to specify the climate sensitivity with [an] uncertainty range appreciably narrower than it is at present." Indeed, he says "the need for reducing the uncertainty from its present estimated value by *at least a factor of 3* and perhaps *a factor of 10 or more* seems *inescapable* [all our italics] if the uncertainty in climate sensitivity is to be reduced to an extent where it becomes useful for formulating policy to deal with global change," which surely suggests that even the best climate models of the day are wholly inadequate for this purpose.

Coming to much the same conclusion was the study of Jaenicke *et al.* (2007), who reviewed the status of research being conducted on biological materials in the atmosphere, which they denominate *primary biological atmospheric particles* or PBAPs. Originally, these particles were restricted to *culture forming units*, including pollen, bacteria, mold and viruses, but they also include fragments of living and dead organisms and plant debris, human and animal epithelial cells, broken hair filaments, parts of insects, shed feather fractions, etc., which they lump together under the category of *dead biological matter*.

With respect to the meteorological and climatic relevance of these particles, they note that many PBAPs, including "decaying vegetation, marine plankton and bacteria are excellent ice nuclei," and they say that "one can easily imagine the[ir] influence on cloud cover, climate forcing and feedback and global precipitation distribution."

In describing their own measurements and those of others, which they say "have now been carried out at several geographical locations covering all seasons of the year and many characteristic environments," Jaenicke *et al.* report that "by number and volume, the PBAP fraction is ~20% of the total aerosol, and appears rather constant during the year." In addition, they write that "the impression prevails that the biological material, whether produced directly or shed during the seasons, sits on surfaces, ready to be lifted again in resuspension."

In a brief summation of their findings, the German researchers say "the overall conclusion can only be that PBAPs are a major fraction of atmospheric aerosols, and are comparable to sea salt over the oceans and mineral particles over the continents," and, consequently, that "the biosphere must be a major source for directly injected biological particles, and those particles should be taken into account in understanding and modeling atmospheric processes." *However*, they note that "the IPCC-Report of 2007 *does not even mention these particles* [our italics and boldface]," and that "this disregard of the biological particles requires a new attitude."

We agree. And we hope that that attitude includes a willingness to acknowledge that, as comprehensive as current state-of-the-art climate models might be, there is much of significance that is not included in them, and that when that which is missing is finally factored in and properly modeled, it could well result in radically different conclusions being reached from those that are currently held by the IPCC.

Our review of important aerosol studies continues below with a separate discussion of four important aerosol categories: (1) Biological (Aquatic), (2) Biological (Terrestrial), (3) Non-Biological (Anthropogenic) and (4) Non-Biological (Natural). Additional information on this topic, including reviews of aerosols not discussed here, can be found at [http://www.co2science.org/subject/a/subject\\_a.php](http://www.co2science.org/subject/a/subject_a.php) under the heading Aerosols.

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### **3.1. Biological (Aquatic)**

Charlson *et al.* (1987) described a multi-stage negative feedback phenomenon - several components of which have been verified by subsequent scientific studies - that links biology with climate change. The process begins with an initial impetus for warming that stimulates primary production in marine phytoplankton. This enhanced process leads to the production of more copious quantities of dimethylsulphoniopropionate, which leads in turn to the evolution of greater amounts of dimethyl sulphide, or DMS, in the surface waters of the world's oceans. Larger quantities of DMS thus diffuse into the atmosphere, where the gas is oxidized, leading to the creation of greater amounts of acidic aerosols that function as cloud condensation nuclei. This phenomenon then leads to the creation of more and brighter clouds that reflect more incoming solar radiation back to space, thereby providing a cooling influence that counters the initial impetus for warming.

Several recent studies have shed additional light on this complex hypothesis. Simo and Pedros-Alio (1999), for example, used satellite imagery and *in situ* experiments to study the production of DMS by enzymatic cleavage of dimethylsulphoniopropionate in the North Atlantic Ocean about 400 km south of Iceland, finding that the depth of the surface mixing-layer has a substantial influence on DMS yield in the short term, as do seasonal variations in vertical mixing in the longer term, which observations led them to conclude that "climate-controlled mixing controls DMS production over vast regions of the ocean."

Amplifying the significance of this finding, Hopke *et al.* (1999) analyzed weekly concentrations of 24 different airborne particulates measured at the northernmost manned site in the world - Alert, Northwest Territories, Canada - from 1980 to 1991. One of their more interesting discoveries was the finding that concentrations of biogenic sulfur, including sulfate and methane sulfonate, were low in winter but high in summer, and that the year-to-year variability in the strength of the biogenic sulfur signal was strongly correlated with the mean temperature of the Northern Hemisphere. "This result," as the authors say, "suggests that as the temperature rises, there is increased biogenic production of the reduced sulfur precursor compounds that are oxidized in the atmosphere to sulfate and methane sulfonate and could be evidence of a negative feedback mechanism in the global climate system."

Further support for this aquatic life-climate linkage was provided by Ayers and Gillett (2000), who summarized relevant empirical evidence collected at Cape Grim, Tasmania, along with pertinent evidence reported in many peer-reviewed scientific papers on the subject. This exercise led them to conclude that "major links in the feedback chain proposed by Charlson *et al.* (1987) have a sound physical basis." More specifically, they noted there is "compelling observational evidence to suggest that DMS and its atmospheric products participate significantly in processes of climate regulation and reactive atmospheric chemistry in the remote marine boundary layer of the Southern Hemisphere."

In another test of the Charlson *et al.* hypothesis, Sciare *et al.* (2000) made continuous measurements of atmospheric DMS concentration over the 10-year period 1990-1999 at Amsterdam Island in the southern Indian Ocean. Their study revealed "a clear seasonal

variation with a factor of 20 in amplitude between its maximum in January (austral summer) and minimum in July-August (austral winter)." In addition, they found DMS anomalies to be "closely related to sea surface temperature anomalies, clearly indicating a link between DMS and climate changes." In fact, they found that a temperature increase of only 1°C was sufficient to increase the atmospheric DMS concentration by as much as 50% on a monthly basis, noting that "this is the first time that a direct link between SSTs [sea surface temperatures] and atmospheric DMS is established for a large oceanic area."

In a related study, Baboukas *et al.* (2002) report the results of nine years of measurements of methanesulfonate ( $\text{MS}^-$ ), an exclusive oxidation product of DMS, in *rainwater* at Amsterdam Island. Their data, too, reveal "a well distinguished seasonal variation with higher values in summer, in line with the seasonal variation of its gaseous precursor (DMS)," which, as they say, "further confirms the findings of Sciare *et al.* (2000)." In addition, the  $\text{MS}^-$  anomalies in the rainwater were found to be closely related to sea surface temperature anomalies; and the authors say this observation provides even more support for "the existence of a positive ocean-atmosphere feedback on the biogenic sulfur cycle above the Austral Ocean, one of the most important DMS sources of the world."

Another pertinent study was conducted by Kouvarakis and Mihalopoulos (2002), who investigated the seasonal variations of gaseous dimethylsulfide (DMS) and its oxidation products - non-sea-salt sulfate ( $\text{nss-SO}_4^{2-}$ ) and methanesulfonic acid (MSA) - at a remote coastal location in the Eastern Mediterranean Sea from May 1997 through October 1999, as well as the diurnal variation of DMS during two intensive measurement campaigns in September 1997. In the seasonal investigation, DMS concentrations tracked sea surface temperature (SST) almost perfectly, going from a low of 0.87  $\text{nmol m}^{-3}$  in the winter to a high of 3.74  $\text{nmol m}^{-3}$  in the summer. Such was also the case in the diurnal study: DMS concentrations were lowest just before sunrise, rose rapidly thereafter to about 1100, were followed by a little dip and then a further rise to 2000, whereupon a decline set in that continued until just before sunrise. MSA concentrations exhibited a similar seasonal variation to that displayed by DMS, ranging from a wintertime low of 0.04  $\text{nmol m}^{-3}$  to a summertime high of 0.99  $\text{nmol m}^{-3}$ . The same was also true of aerosol  $\text{nss-SO}_4^{2-}$ , which varied from 0.6 to 123.9  $\text{nmol m}^{-3}$  in going from winter to summer.

As time marches on, therefore, and as ever more studies of the Charlson *et al.* hypothesis are conducted (O'Dowd *et al.*, 2004; Toole and Siegel, 2004), it is becoming ever more clear that the normal hour-to hour, day-to-day and season-to-season behaviors of the phytoplanktonic inhabitants of earth's marine ecosystems effectively combat extreme environmental temperature changes; and in view of their efficacy, it would seem we have little to worry about in the way of catastrophic  $\text{CO}_2$ -induced global warming.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/a/aerosolsbioaqua.php>.

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### **3.2. Biological (Terrestrial)**

Just as marine phytoplankton that are exposed to rising temperatures give off greater quantities of gases that lead to the production of greater quantities of cloud condensation nuclei, which create more and brighter clouds that reflect more incoming solar radiation back to space and thereby either reverse, stop or slow the warming that initiated this negative feedback phenomenon, so too do terrestrial plants respond in like manner, thereby enhancing their ability to survive in a changing global environment. What is more, earth's terrestrial plants have a tendency to operate in this manner ever more effectively as the air's CO<sub>2</sub> content rises ever higher.

A good introduction to this subject is provided by the review paper of Peñuelas and Llusia (2003), who say that *biogenic volatile organic compounds* -- or BVOCs -- constitute "one of nature's biodiversity treasures." Comprised of isoprene, terpenes, alkanes, alkenes, alcohols, esters, carbonyls and acids, this diverse group of substances is produced by a variety of processes occurring in many plant tissues. Some of the functions of these substances, according to the two scientists, include acting as "deterrents against pathogens and herbivores, or to aid wound sealing after damage (Pichersky and Gershenzon, 2002)." They also say that BVOCs provide a means "to attract pollinators and herbivore predators, and to communicate with other plants and organisms (Peñuelas *et al.*, 1995; Shulaev *et al.*, 1997)."

Of particular importance within the context of global climate change, in the opinion of Peñuelas and Llusia, is the growing realization that "isoprene and monoterpenes, which constitute a major fraction of BVOCs, might confer protection against high temperatures" by acting "as scavengers of reactive oxygen species produced [within plants] under high temperatures." If this is indeed the case, it can be appreciated that with respect to the claimed ill effects of CO<sub>2</sub>-induced global warming on earth's vegetation, there are likely to be two strong ameliorative phenomena that act to protect the planet's plants: (1) the aerial fertilization effect of atmospheric CO<sub>2</sub> enrichment, which is typically more strongly expressed at higher temperatures, and (2) the tendency for rising air temperatures and CO<sub>2</sub> concentrations to spur the production of higher concentrations of heat-stress-reducing BVOCs. With respect to temperature, for example, Peñuelas and Llusia calculate that "global warming over the past 30 years could have increased the BVOC global emissions by approximately 10%, and a further 2-3°C rise in the mean global temperature ... could increase BVOC global emissions by an additional 30-45%."

There may also be a couple of other phenomena that favor earth's plants within this context. Peñuelas and Llusia note, for example, that "the increased release of nitrogen into the biosphere by man probably also enhances BVOC emissions by increasing the level of carbon fixation and the activity of the responsible enzymes (Litvak *et al.*, 1996)." In addition, they indicate that the conversion of abandoned agricultural lands to forests and the implementation of planned reforestation projects should help the rest of the biosphere too, reporting that additional numbers of "*Populus*, *Eucalyptus* or *Pinus*, which are major emitters, might greatly increase BVOC emissions."

Most intriguing of all, perhaps, is how increased BVOC emissions might impact climate change. Peñuelas and Llusia say that "BVOCs generate large quantities of organic aerosols that could affect climate significantly by forming cloud condensation nuclei." As a result, they say "there should be a net cooling of the Earth's surface during the day because of radiation interception," noting that Shallcross and Monks (2000) "have suggested that one of the reasons plants emit the aerosol isoprene might be to cool the surroundings in addition to any physiological or evaporative effects that might cool the plant directly."

However, not all experiments have reported increases in plant BVOC emissions with increasing atmospheric CO<sub>2</sub> concentrations, one example being that of Constable *et al.* (1999), who found

no effect of elevated CO<sub>2</sub> on monoterpene emissions from Ponderosa pine and Douglas fir trees. Some studies, in fact, have even reported *decreases* in BVOC emissions, such as those of Vuorinen *et al.* (2004), who worked with cabbage plants, and Loreto *et al.* (2001), who studied monoterpene emissions from oak seedlings. On the other hand, Staudt *et al.* (2001) observed CO<sub>2</sub>-induced *increases* in BVOC emissions in *the identical species of oak*. An explanation for this wide range of results comes from Baraldi *et al.* (2004), who -- after exposing sections of a southern California chaparral ecosystem to atmospheric CO<sub>2</sub> concentrations ranging from 250 to 750 ppm in 100-ppm increments for a period of four years -- concluded that "BVOC emission can remain nearly constant as rising CO<sub>2</sub> reduces emission per unit leaf area while stimulating biomass growth and leaf area per unit ground area." In most of the cases investigated, however, BVOC emissions tend to increase with atmospheric CO<sub>2</sub> enrichment; and the increases are often huge.

A case in point is provided by the study of Jasoni *et al.* (2003), who grew onions from seed for 30 days in individual cylindrical flow-through growth chambers under controlled environmental conditions at atmospheric CO<sub>2</sub> concentrations of either 400 or 1000 ppm. At the end of the study, the plants in the CO<sub>2</sub>-enriched chambers had 40% more biomass than the plants grown in ambient air, and their photosynthetic rates were 22% greater. In addition, the CO<sub>2</sub>-enriched plants exhibited *17-fold* and *38-fold* increases in emissions of the BVOC hydrocarbons 2-undecanone and 2-tridecanone, respectively, which Jasoni *et al.* make a point of noting "confer insect resistance against a major agricultural pest, spider mites." More generally, they conclude that "plants grown under elevated CO<sub>2</sub> will accumulate excess carbon and that at least a portion of this excess carbon is funneled into an increased production of BVOCs," which have many positive implications in the realms of both biology and climate, as noted above.

Another example is seen in the study of Raisanen *et al.* (2008), who developed an experiment designed to see to what extent a doubling of the air's CO<sub>2</sub> content and a 2-6°C increase in air temperature might impact the emission of monoterpenes from 20-year-old Scots pine (*Pinus sylvestris* L.) seedlings, Raisanen *et al.* (2008) studied the two phenomena (and their interaction) within closed-top chambers built on a naturally-seeded stand of the trees in eastern Finland that had been exposed to the four treatments -- ambient CO<sub>2</sub> and ambient temperature, ambient temperature and elevated CO<sub>2</sub>, ambient CO<sub>2</sub> and elevated temperature, elevated temperature and elevated CO<sub>2</sub>-- for the prior five years.

Over the five-month growing season of May-September, the three Finnish researchers found that total monoterpene emissions in the elevated-CO<sub>2</sub>-only treatment were 5% greater than those in the ambient CO<sub>2</sub>, ambient temperature treatment, and that emissions in the elevated-temperature-only treatment were 9% less than those in ambient air. In the presence of both elevated CO<sub>2</sub> and elevated temperature, however, there was an increase of fully 126% in the total amount of monoterpenes emitted over the growing season, which led the authors to conclude that "the amount of monoterpenes released by Scots pines into the atmosphere during a growing season will increase substantially in the predicted future climate."



A number of studies suggest that the phenomena discussed in the preceding paragraphs do indeed operate in the real world. Kavouras *et al.* (1998), for example, measured a number of atmospheric gases and particles in a eucalyptus forest in Portugal and analyzed their observations to see if there was any evidence of biologically-produced gases being converted to particles that could function as cloud condensation nuclei. Their work demonstrated that certain hydrocarbons emitted by vegetation (isoprene and terpenes, in particular) do indeed experience gas-to-particle transformations. In fact, aerosols (or *biosols*) produced from two of these organic acids (*cis*- and *trans*-pinonic acid) comprised as much as 40% of the fine particle atmospheric mass during daytime hours.

These findings clearly demonstrate that the *biology* of the earth can indeed influence the *climate* of the earth. Specifically, they reveal a direct connection between the metabolic activity of trees and the propensity for the atmosphere to produce clouds. What is more, the relationship is one that is self-protecting of the biosphere: as the air's CO<sub>2</sub> content rises, plant productivity rises, which leads to an enhanced evolution of biogenic gases, which leads to the production of more cloud condensation nuclei, which leads to the creation of more clouds that reflect more solar radiation back to space, which tends to counter any increase in the strength of the atmosphere's greenhouse effect that may have been produced by the initial rise in the air's CO<sub>2</sub> content.

A similar study was conducted by O'Dowd *et al.* (2002), who measured aerosol electrical-mobility size-distributions before and during the initial stage of an atmospheric nucleation event over a boreal forest in Finland. Simultaneously, organic vapor growth rate measurements were made of particles that nucleated into organic cloud-droplets in the flow-tube cloud chamber of a modified condensation-particle counter. This work demonstrated, in their words, that newly-formed aerosol particles over forested areas "are composed primarily of organic species, such as *cis*-pinonic acid and pinonic acid, produced by oxidation of terpenes in organic vapours released from the canopy."

Commenting on this finding, O'Dowd *et al.* note that "aerosol particles produced over forested areas may affect climate by acting as nuclei for cloud condensation," but they say there remain numerous uncertainties involving complex feedback processes "that must be determined if we are to predict future changes in global climate." This being the case, we wonder how anyone can presume to decide what should or should not be done about anthropogenic CO<sub>2</sub> emissions; for if we can't predict future changes in global climate without the knowledge just specified, how do we know if we even need to be worried about the matter?

Shifting from trees to a much tinier plant, Kuhn and Kesselmeier (2000) collected lichens from an open oak woodland in central California, USA, and studied their uptake of carbonyl sulfide or COS in a dynamic cuvette system under controlled conditions in the laboratory. When optimally hydrated, COS was absorbed from the atmosphere by the lichens at a rate that gradually doubled as air temperature rose from approximately 3 to 25°C, whereupon the rate of COS absorption dropped precipitously, reaching a value of zero at 35°C. Why is this significant?

COS is the most stable and abundant reduced sulfur gas in the atmosphere and is thus a major player in determining earth's radiation budget. After making its way into the stratosphere, it can be photo-dissociated, as well as oxidized, to form SO<sub>2</sub>, which is typically converted to sulfate aerosol particles that are highly reflective of incoming solar radiation and, therefore, have the capacity to significantly cool the earth as more and more of them collect above the tropopause. This being the case, it is only natural to suspect that biologically-modulated COS concentrations may play a role in keeping earth's surface air temperature within bounds conducive to the continued existence of life; and that is exactly what is implied by the observations of Kuhn and Kesselmeier. Once air temperature rises above 25°C, the rate of removal of COS from the air by this particular species of lichen declines dramatically; and when this happens, more COS remains in the air, which increases the potential for more COS to make its way into the stratosphere, where it can be converted into sulfate aerosol particles that can reflect more incoming solar radiation back to space and thereby cool the earth. And since the consumption of COS by lichens is under the physiological control of carbonic anhydrase -- which is the key enzyme for COS uptake in all higher plants, algae and soil organisms -- we could expect this phenomenon to be generally operative throughout much of the plant kingdom. Hence, this biological "thermostat" may well be powerful enough to define an upper limit above which the surface air temperature of the planet may be restricted from rising, even when changes in other forcing factors, such as greenhouse gases, produce an impetus for it to do so.

Although BVOCs emitted from terrestrial plants both small and large are thus important to earth's climate, trees tend to dominate in this regard; and recent research suggests yet another way in which their response to atmospheric CO<sub>2</sub> enrichment may provide an effective counterbalance to the greenhouse properties of CO<sub>2</sub>. The phenomenon begins with the propensity for CO<sub>2</sub>-induced increases in BVOCs, together with the cloud particles they spawn, to enhance the amount of diffuse solar radiation reaching the earth's surface (Suraqui *et al.*, 1974; Abakumova *et al.*, 1996), which is followed by the ability of enhanced diffuse lighting to reduce the volume of shade within vegetative canopies (Roderick *et al.*, 2001), which is followed by the tendency for less internal canopy shading to enhance whole-canopy photosynthesis (Healey *et al.*, 1998), which finally produces the end result: a greater photosynthetic extraction of CO<sub>2</sub> from the air and the subsequent reduction of the strength of the atmosphere's greenhouse effect.

How significant is this process? Roderick *et al.* provide a good estimate based on the utilization of a unique "natural experiment," a technique that has been used extensively by Idso (1998) to evaluate the overall climatic sensitivity of the planet. Specifically, Roderick and his colleagues consider the volcanic eruption of Mt. Pinatubo in June of 1991. This event ejected enough gases and fine materials into the atmosphere that it produced sufficient aerosol particles to greatly increase the diffuse component of the solar radiation reaching the surface of the earth from that point in time through much of 1993, while only slightly reducing the receipt of total solar radiation.

Based on a set of lengthy calculations, Roderick *et al.* concluded that the Mt. Pinatubo eruption may well have resulted in the removal of an extra 2.5 Gt of carbon from the atmosphere due to its diffuse-light-enhancing stimulation of terrestrial photosynthesis in the year following the eruption, which would have reduced the ongoing rise in the air's CO<sub>2</sub> concentration that year by about 1.2 ppm. Interestingly, this reduction is about the size of the real-world reduction that was measured that year (Sarmiento, 1993). What makes this observation even more impressive is the fact that the CO<sub>2</sub> reduction was coincident with an El Niño event; because, in the words of Roderick *et al.*, "previous and subsequent such events have been associated with *increases* in atmospheric CO<sub>2</sub>." In addition, the observed reduction in total solar radiation received at the earth's surface during this period would have had a tendency to reduce the amount of photosynthetically active radiation incident upon earth's plants, which would also have had a tendency to cause the air's CO<sub>2</sub> content to rise, as it would tend to lessen global photosynthetic activity.

Additional real-world evidence for the existence of this phenomenon was provided by Gu *et al.* (2003), who reported using "two independent and direct methods to examine the photosynthetic response of a northern hardwood forest (Harvard Forest, 42.5°N, 72.2°W) to changes in diffuse radiation caused by Mount Pinatubo's volcanic aerosols." They found that "around noontime in the midgrowing season, the gross photosynthetic rate under the perturbed cloudless solar radiation regime was 23, 8, and 4% higher than that under the normal cloudless solar radiation regime in 1992, 1993, and 1994, respectively," and that "integrated over a day, the enhancement for canopy gross photosynthesis by the volcanic aerosols was 21% in 1992, 6% in 1993 and 3% in 1994." In reflecting on the significance of these observations, Gu *et al.* stated that "because of substantial increases in diffuse radiation world-wide after the eruption and strong positive effects of diffuse radiation for a variety of vegetation types, it is likely that our findings at Harvard Forest represent a global phenomenon."

As impressive as these findings are, Gu *et al.* did not stop there. They went on to document a powerful propensity for the extra diffuse light created by increased *cloud cover* to *further* enhance forest photosynthesis, and to do so even though the total flux of solar radiation received at the earth's surface is typically significantly *reduced* under such conditions (Stanhill and Cohen, 2001). Based on still more real-world data, for example, they reported finding that "Harvard Forest photosynthesis also increases with cloud cover, with a peak at about 50% cloud cover."

In all of the original investigations of this phenomenon, which also include the studies of Law *et al.* (2002), Farquhar and Roderick (2003) and Reichenau and Esser (2003), the source of the enhanced aerosol concentration, i.e., the key *natural experiment*, was a massive volcanic eruption. So what happens under more normal conditions? This is the question that was asked by Niyogi *et al.* (2004): "can we detect the effect of relatively routine aerosol variability on field measurements of CO<sub>2</sub> fluxes, and if so, how does the variability in aerosol loading affect CO<sub>2</sub> fluxes over different landscapes?"

To answer this question, the group of sixteen researchers used CO<sub>2</sub> flux data from the AmeriFlux network (Baldocchi *et al.*, 2001) together with cloud-free aerosol optical depth data from the NASA Robotic Network (AERONET; Holben *et al.*, 2001) to assess the effect of aerosol loading on the net assimilation of CO<sub>2</sub> by three types of vegetation: trees (broadleaf deciduous forest and mixed forest), crops (winter wheat, soybeans and corn) and grasslands. Their work revealed that an aerosol-induced increase in *diffuse radiative-flux fraction* [DRF = ratio of diffuse (R<sub>d</sub>) to total or global (R<sub>g</sub>) solar irradiance] increased the net CO<sub>2</sub> assimilation of trees and crops, making them larger carbon sinks, but that it decreased the net CO<sub>2</sub> assimilation of grasslands, making them smaller carbon sinks.

How significant were the effects observed by Niyogi *et al.*? For a summer mid-range R<sub>g</sub> flux of 500 W m<sup>-2</sup>, going from the set of all DRF values between 0.0 and 0.4 to the set of all DRF values between 0.6 and 1.0 resulted in an approximate 50% increase in net CO<sub>2</sub> assimilation by a broadleaf deciduous forest located in Tennessee, USA. Averaged over the entire daylight period, they further determined that the shift from the lower to the higher set of DRF values "enhances photosynthetic fluxes by about 30% at this study site." Similar results were obtained for the mixed forest and the conglomerate of crops studied. Hence, they concluded that natural variability among commonly-present aerosols can "routinely influence surface irradiance and hence the terrestrial CO<sub>2</sub> flux and regional carbon cycle." For these types of land-cover (forests and agricultural crops), that influence is to significantly *increase* the assimilation of CO<sub>2</sub> from the atmosphere; and this effect greatly overpowers the opposite effect that occurs over grasslands, primarily because earth's trees and shrubs are responsible for fully two thirds of the planet's net primary production.

What is especially exciting about these real-world observations is that much of the commonly-present aerosol burden of the atmosphere is plant-derived. Hence, it can be appreciated that earth's woody plants are themselves responsible for emitting to the air that which ultimately enhances their photosynthetic prowess. In other words, earth's trees significantly control their own destiny, i.e., they alter the atmospheric environment in a way that directly enhances their opportunities for greater growth.

Humanity also helps in this regard; for as we pump ever more CO<sub>2</sub> into the atmosphere, the globe's woody plants quickly respond to its *aerial fertilization effect*, becoming ever more productive, which leads to even more plant-derived aerosols being released to the atmosphere, which stimulates this positive feedback cycle to a still greater degree. Stated another way, earth's trees use some of the CO<sub>2</sub> emitted to the atmosphere by man to alter the aerial environment so as to enable them to remove even more CO<sub>2</sub> from the air. The end result is that earth's trees and humanity are working *hand-in-hand* to significantly increase the productivity of the biosphere; and it is happening in spite of all of the *true* anthropogenic insults to the environment that work in opposition to enhanced biological activity.

In light of these several observations, it should be painfully obvious that the historical and still-ongoing CO<sub>2</sub>-induced increase in atmospheric BVOCs should have had, and should be continuing to have, a significant cooling effect on the planet that exerts itself by both slowing

the rate of rise of the air's CO<sub>2</sub> content and reducing the receipt of solar radiation at the earth's surface, neither of which effects is included in any general circulation model of the atmosphere of which we are aware.

One final beneficial effect of CO<sub>2</sub>-induced increases in BVOC emissions is described by Goldstein *et al.* (2004), and that is the propensity of BVOCs to destroy tropospheric ozone.

As a bit of a background, earth's vegetation is responsible for the production of vast amounts of ozone (O<sub>3</sub>; Chameides *et al.*, 1988; Harley *et al.*, 1999), but it is also responsible for *destroying* a lot of O<sub>3</sub>. With respect to the latter phenomenon, Goldstein *et al.* mention three major routes by which O<sub>3</sub> exits the air near the earth's surface: leaf stomatal uptake, surface deposition, and within-canopy gas-phase chemical reactions with BVOCs. The first of these exit routes, according to them, accounts for 30-90% of total ecosystem O<sub>3</sub> uptake from the atmosphere (= O<sub>3</sub> destruction), while the remainder has typically been attributed to deposition on non-stomatal surfaces. However, they note that "Kurpius and Goldstein (2003) recently showed that the non-stomatal flux [from the atmosphere to oblivion] increased exponentially as a function of temperature at a coniferous forest site," and that "the exponential increase with temperature was consistent with the temperature dependence of monoterpene emissions from the same ecosystem, suggesting O<sub>3</sub> was lost via gas phase reactions with biogenically emitted terpenes before they could escape the forest canopy."

In a study designed to take the next step towards turning the implication of this observation into something stronger than a mere suggestion, Schade and Goldstein (2003) demonstrated that forest thinning dramatically enhances monoterpene emissions. In the current study, Goldstein *et al.* take another important step towards clarifying the issue by measuring the effect of forest thinning on O<sub>3</sub> destruction in an attempt to see if it is enhanced in parallel fashion to the thinning-induced increase in monoterpene emissions.

In a ponderosa pine plantation in the Sierra Nevada Mountains of California, USA, a management procedure to improve forest health and optimize tree growth was initiated on 11 May and continued through 15 June 2000. This procedure involved the use of a *masticator* to mechanically "chew up" smaller unwanted trees and leave their debris on site, which operation reduced plantation green leaf biomass by just over half. Simultaneously, monoterpene mixing ratios and fluxes were measured hourly within the plantation canopy, while total ecosystem O<sub>3</sub> destruction was "partitioned to differentiate loss due to gas-phase chemistry from stomatal uptake and deposition."

Goldstein *et al.* report that both the destruction of ozone due to gas-phase chemistry and emissions of monoterpenes increased dramatically with the onset of thinning, and that these phenomena continued in phase with each other thereafter. Hence, they "infer that the massive increase of O<sub>3</sub> flux [from the atmosphere to oblivion] during and following mastication is driven by loss of O<sub>3</sub> through chemical reactions with unmeasured terpenes or closely related BVOCs whose emissions were enhanced due to wounding [by the masticator]." Indeed, they say that "considered together, these observations provide a conclusive picture that the chemical loss of

O<sub>3</sub> is due to reactions with BVOCs emitted in a similar manner as terpenes," and that "we can conceive no other possible explanation for this behavior other than chemical O<sub>3</sub> destruction in and above the forest canopy by reactions with BVOCs."

Goldstein *et al.* say their results "suggest that total reactive terpene emissions might be roughly a factor of 10 higher than the typically measured and modeled monoterpene emissions, making them larger than isoprene emissions on a global scale." If this proves to be the case, it will be a most important finding, for it would mean that vegetative emissions of terpenes, which lead to the *destruction* of ozone, are significantly greater than vegetative emissions of isoprene, which lead to the *creation* of ozone (Poisson *et al.*, 2000). In addition, there is substantial evidence to suggest that the ongoing rise in the air's CO<sub>2</sub> content may well lead to an overall *reduction* in vegetative *isoprene* emissions, while at the same time enhancing vegetative productivity, which may well lead to an overall *increase* in vegetative *terpene* emissions. As a result, there is reason to believe that the ongoing rise in the air's CO<sub>2</sub> content will help to reduce the ongoing rise in the air's O<sub>3</sub> concentration, which should be a boon to the entire biosphere.

In conclusion, a wealth of real-world evidence is beginning to suggest that both rising air temperatures and CO<sub>2</sub> concentrations significantly increase desirable vegetative BVOC emissions, particularly from trees, which constitute the most prominent photosynthetic force on the planet, and that this phenomenon has a large number of extremely important and highly beneficial biospheric consequences.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/a/aerosolsterr.php>.

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### **3.3. Non-Biological (Anthropogenic)**

There are also numerous ways in which the activities of humanity lead to the creation of aerosols that have the potential to alter earth's radiation balance and affect its climate. Contrails created in the wake of emissions from jet aircraft are one example, where Minnis *et al.* (2004) have calculated that nearly all of the surface warming observed over the United States between 1975 and 1994 (0.54°C) may well be explained by aircraft-induced increases in cirrus cloud coverage over that period. If true, this result would imply that *little to none* of the observed U.S. warming over that period could be attributed to the concomitant increase in the air's CO<sub>2</sub> content. *Ship tracks*, or bright streaks that form in layers of marine stratus clouds, are another example. They are created by emissions from ocean-going vessels; and these persistent and highly-reflective linear patches of low-level clouds generally always tend to cool the planet (Ferek *et al.*, 1998; Schreier *et al.*, 2006). Averaged over the surface of the earth both day and night and over the year, for example, Capaldo *et al.* (1999) have calculated that this phenomenon creates a mean *negative* radiative forcing of -0.16 Wm<sup>-2</sup> in the Northern Hemisphere and -0.06 Wm<sup>-2</sup> in the Southern Hemisphere, which values are to be compared to the much larger *positive* radiative forcing of approximately 4 Wm<sup>-2</sup> due to a 300 ppm increase in the atmosphere's CO<sub>2</sub> concentration.

In some cases, the atmosphere over the sea also carries a considerable burden of anthropogenically-produced aerosols that come from terrestrial sites. In recent years, attention to this topic has centered on highly-polluted air from south and southeast Asia that makes its way over the northern Indian Ocean during the dry monsoon season. There has been much discussion about the impact of this phenomenon on regional climate; and within this context, Norris (2001) has looked at cloud cover as the ultimate arbiter of the various competing hypotheses, finding that daytime low-level oceanic cloud cover increased substantially over the last half of the past century in both the Northern and Southern Hemispheres at essentially all hours of the day. This finding is indicative of a pervasive net cooling effect.

Over land, aerosol-generating human activities also have a significant impact on local, as well as more wide-ranging, climatic phenomena. Most interesting in the local context is the study of Sahai (1998), who found that although suburban areas of Nagpur, India had warmed over recent decades, the central part of the city had cooled, especially during the day, because of "increasing concentrations of suspended particulate matter." Likewise, outside of, but adjacent to, industrial complexes in the Po Valley of Italy, Facchini *et al.* (1999) found that water vapor was more likely to form on aerosols that had been altered by human-produced organic solutes, and that this phenomenon led to the creation of more numerous and more-highly-reflective cloud droplets that had a tendency to cool the surface below them.

In a similar vein, Rosenfield (2000) studied terrestrial analogues of ship tracks downwind of urban/industrial complexes in Turkey, Canada and Australia, to which he gave the name *pollution tracks*. His findings indicated that the clouds comprising these pollution tracks were composed of droplets of reduced size that suppressed precipitation by inhibiting further coalescence and ice precipitation formation. In commenting on this research, Toon (2000) pointed out that when clouds are composed of smaller droplets, they will not "rain out" as quickly and will therefore last longer and cover more of the earth, both of which effects tend to cool the globe.

In reviewing these and other advances in the field of anthropogenic aerosol impacts on clouds, Charlson *et al.* (2001) note that droplet clouds "are the most important factor controlling the albedo (reflectivity) and hence the temperature of our planet." Furthermore, he and his coauthors state that man-made aerosols "have a strong influence on cloud albedo, with a global mean forcing estimated to be of the same order (but opposite in sign) as that of greenhouse gases." In fact, in reviewing the very newest advances in this field of research, which have yet to be incorporated into either the analyses or recommendations of the Intergovernmental Panel on Climate Change, Charlson *et al.* conclude that "both the forcing [of this man-induced impetus for cooling] and its magnitude may be even larger than anticipated." Hence, they rightly warn us that lack of inclusion of the consequences of these important phenomena in climate change deliberations "poses additional uncertainty beyond that already recognized by the Intergovernmental Panel on Climate Change, making the largest uncertainty in estimating climate forcing even larger."

Another assessment of the issue was provided by Ghan *et al.* (2001), who studied both the *positive* radiative forcings of *greenhouse gases* and the *negative* radiative forcings of *anthropogenic aerosols* and reported that current best estimates of "the total global mean present-day anthropogenic forcing range from  $3 \text{ Wm}^{-2}$  to  $-1 \text{ Wm}^{-2}$ ," which represents everything from a modest warming to a slight cooling. After performing their own analysis of the problem, they reduced the magnitude of this range somewhat; but the end result still stretched from a small cooling influence to a modest impetus for warming. "Clearly," they thus concluded, "the great uncertainty in the radiative forcing must be reduced if the observed climate record is to be reconciled with model predictions and if estimates of future climate change are to be useful in formulating emission policies."

Another pertinent observation comes from Stanhill and Cohen (2001), who reviewed numerous solar radiation measurement programs around the world to see if there had been any trend in the mean amount of solar radiation falling on the surface of the earth over the past half-century. In a finding so stunning that it stretches one's credulity, they determined there was a significant 50-year downward trend in this parameter that "has globally averaged  $0.51 \pm 0.05 \text{ Wm}^{-2}$  per year, equivalent to a reduction of 2.7% per decade, [which] now totals  $20 \text{ Wm}^{-2}$ ." They also concluded that the most probable explanation for this observation "is that increases in man made aerosols and other air pollutants have changed the optical properties of the atmosphere, in particular those of clouds."

Although this surface-cooling influence is huge, it falls right in the mid-range of a similar solar radiative perturbation documented by Satheesh and Ramanathan (2000) in their study of the effects of human-induced pollution over the tropical northern Indian Ocean, where they determined that "mean clear-sky solar radiative heating for the winters of 1998 and 1999 decreased at the ocean surface by 12 to  $30 \text{ Wm}^{-2}$ ." Hence, the decline in solar radiation reception discovered by Stanhill and Cohen could well be real. And if it is, it represents a *tremendous* counter-influence to the enhanced greenhouse effect produced by the contemporaneous increase in atmospheric  $\text{CO}_2$  concentration. In fact, it overwhelms it.

Finally, we turn to a more recent study by Ruckstuhl *et al.* (2008), who presented "observational evidence of a strong *decline* [our italics] in aerosol optical depth over mainland Europe during the last two decades of rapid warming" -- when air temperatures rose by about  $1^\circ\text{C}$  after 1980 -- via analyses of "aerosol optical depth measurements from six specific locations and surface irradiance measurements from a large number of radiation sites in Northern Germany and Switzerland."

In consequence of the observed decline in aerosol concentration of up to 60%, the authors' state there was "a statistically significant increase of solar irradiance under cloud-free skies since the 1980s." The value of the direct aerosol effect of this radiative forcing was approximately  $0.84 \text{ Wm}^{-2}$ ; and when combined with the concomitant cloud-induced radiative forcing of about  $0.16 \text{ Wm}^{-2}$ , it lead to a total radiative surface climate forcing over mainland Europe of about  $1 \text{ Wm}^{-2}$  that "most probably strongly contributed to the recent rapid warming in Europe."

Cleaning up significantly polluted skies can provide an even greater impetus for climate warming than does the carbon dioxide that is concurrently emitted to them, as has apparently been the case over mainland Europe for the past quarter century. Given such findings, it may not be correct to fully ascribe the high temperatures the continent has experienced in recent years to the concomitant ongoing rise in the air's  $\text{CO}_2$  content. The lion's share of the warming has likely been produced by the removal from the atmosphere of *true* air pollutants.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/a/aerononbioanthro.php>.

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### **3.4. Non-Biological (Natural)**

We conclude our section on aerosols with a brief discussion of a non-biological, naturally-produced aerosol -- dust. Dust is about as natural and ubiquitous a substance as there is. Hence, one would think we would have a pretty good handle on what it does to earth's climate as it is moved about by the planet's ever-active atmosphere. But, alas, such is not the case, as was made strikingly clear by Sokolik (1999), who with the help of nine colleagues summarized the sentiments of a number of scientists who have devoted their lives to studying the subject.

The Sokolik-led report notes that state-of-the-art climate models "rely heavily on oversimplified parameterizations" of many important dust-related phenomena, "while ignoring others." As a result, the group concludes that "the magnitude and even the sign of dust net direct radiative forcing of climate remains unclear." Now *that's* uncertainty.

Why is this so? According to Sokolik, there are a number of unanswered questions about airborne dust, including: (1) How does one quantify dust emission rates from both natural and anthropogenic (disturbed) sources with required levels of temporal and spatial resolution? (2) How does one accurately determine the composition, size and shape of dust particles from ground-based and aircraft measurements? (3) How does one adequately measure and model light absorption by mineral particles? (4) How does one link the ever-evolving optical, chemical and physical properties of dust to its life cycle in the air? (5) How does one model complex multi-layered aerosol stratification in the dust-laden atmosphere? (6) How does one quantify airborne dust properties from satellite observations?

In discussing these questions, Sokolik makes some interesting observations, noting that: (1) what is currently known (or believed to be known) about dust emissions "is largely from micro-scale experiments and theoretical studies," (2) new global data sets are needed to provide "missing information" on input parameters (such as soil type, surface roughness and soil moisture) required to model dust emission rates, (3) improvements in methods used to determine some of these parameters are also "sorely needed," (4) how to adequately measure

light absorption by mineral particles is still an "outstanding problem," and (5) it "remains unknown how well these measurements represent the light absorption by aerosol particles suspended in the atmosphere."

Considering these many problems, it is easy to understand why Sokolik says that "a challenge remains in relating dust climatology and the processes controlling the evolution of dust at all relevant spatial/temporal scales needed for chemistry and climate models," for until this challenge is met, we will but "see through a glass, darkly," especially when it comes to trying to discern the effects of airborne dust on earth's climate.

In consequence of - or perhaps in spite of - the murky status of the subject, the work goes on; and in tackling one of the chief challenges set forth by Sokolik, Vogelmann *et al.* (2003) reiterate the fact that "mineral aerosols have complex, highly varied optical properties that, for equal loadings, can cause differences in the surface IR flux [of] between 7 and 25  $\text{Wm}^{-2}$  (Sokolik *et al.*, 1998)," while at the same time acknowledging that "only a few large-scale climate models currently consider aerosol IR effects (e.g., Tegen *et al.*, 1996; Jacobson, 2001) despite their potentially large forcing."

In an attempt to rectify this situation, Vogelmann *et al.* "use[d] high-resolution spectra to obtain the IR radiative forcing at the surface for aerosols encountered in the outflow from northeastern Asia," based on measurements made by the Marine-Atmospheric Emitted Radiance Interferometer aboard the NOAA Ship *Ronald H. Brown* during the Aerosol Characterization Experiment-Asia." This work led them to conclude that "daytime surface IR forcings are often a few  $\text{Wm}^{-2}$  and can reach almost 10  $\text{Wm}^{-2}$  for large aerosol loadings," which values, in their words, "are comparable to or larger than the 1 to 2  $\text{Wm}^{-2}$  change in the globally averaged surface IR forcing caused by greenhouse gas increases since pre-industrial times." And in a massive understatement of fact, Vogelmann *et al.* say that these results "highlight the importance of aerosol IR forcing which should be included in climate model simulations."

Another aspect of the dust-climate connection centers on the African Sahel, which has figured prominently in discussions of climate change ever since it began to experience extended drought conditions in the late 1960s and early 70s. Initial studies of the drought attributed it to anthropogenic factors such as overgrazing of the region's fragile grasses, which tends to increase surface albedo, which was envisioned to reduce precipitation, resulting in a further reduction in the region's vegetative cover, and so on (Otterman, 1974; Charney, 1975). This scenario, however, was challenged by Jackson and Idso (1975) and Idso (1977) on the basis of empirical observations; while Lamb (1978) and Folland *et al.* (1986) attributed the drought to large-scale atmospheric circulation changes triggered by multidecadal variations in sea surface temperature.

Building on the insights provided by these latter investigations, Giannini *et al.* (2003) presented evidence based on an ensemble of integrations with a general circulation model of the atmosphere -- *forced only by the observed record of sea surface temperature* -- which suggested that the "variability of rainfall in the Sahel results from the response of the African summer

monsoon to oceanic forcing amplified by land-atmosphere interaction." The success of this analysis led them to conclude that "the recent drying trend in the semi-arid Sahel is attributed to warmer-than-average low-latitude waters around Africa, which, by favoring the establishment of deep convection over the ocean, weaken the continental convergence associated with the monsoon and engender widespread drought from Senegal to Ethiopia." Hence, they further concluded that "the secular change in Sahel rainfall during the past century was not a direct consequence of regional environmental change, anthropogenic in nature or otherwise."

In a companion article, Prospero and Lamb (2003) report that measurements made from 1965 to 1998 in the Barbados trade winds show large interannual changes in the concentration of dust of African origin that are highly anticorrelated with the prior year's rainfall in the Soudano-Sahel. With respect to this subject, they state that the IPCC report of Houghton *et al.* (2001) "assumes that natural dust sources have been effectively constant over the past several hundred years and that all variability is attributable to human land-use impacts." Of this statement, however, they say "there is little firm evidence to support either of these assumptions," and their findings demonstrate why: the IPCC assumptions are simply wrong. Clearly, much remains to be learned about the climatic impacts of dust on both a regional and global scale before placing any high-degree of confidence in the climatic projections of the IPCC.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/a/aerononbionat.php>.

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## 4. CLIMATE OBSERVATIONS

Models predict numerous changes in various climate parameters all across the globe in consequence of earth's rising atmospheric CO<sub>2</sub> concentration, yet some claim the future predictions are fast upon us and that CO<sub>2</sub>-induced global warming is already occurring, citing many climate-related phenomena as proof of their thesis. In this chapter, we examine a number of the most frequently-cited claims, evaluating their validity as reported in the peer-reviewed scientific literature. Due to space constraints, we examine only a few of those claims in this document. A more comprehensive analysis can be found online at *CO<sub>2</sub> Science* (see <http://www.co2science.org/subject/subject.php>) by selecting a topic of interest in their Subject Index.

### **4.1. Glaciers**

Model studies indicate that CO<sub>2</sub>-induced global warming will result in significant melting of earth's glaciers, contributing to a rise in global sea level. In this section, we examine observational trends in glaciers to see if they match with the model projections. Additional information on this topic, including reviews of glaciers not discussed here, can be found at [http://www.co2science.org/subject/g/subject\\_g.php](http://www.co2science.org/subject/g/subject_g.php) under the heading Glaciers.

#### **4.1.1. Global**

The advance/buildup or retreat/melting of glacial ice is often interpreted as a sign of climate change; and teams of glaciologists have been working for years to provide an assessment of the state of the world's many glaciers as one of several approaches to deciphering global climate trends. Although this effort has only scratched the surface of what must ultimately be done, many have already rendered their verdict: there has been a massive and widespread retreat of glaciers over the past century, which they predict will only intensify under continued CO<sub>2</sub>-induced global warming. This assessment, however, may be a bit premature.

The full story must begin with a clear recognition of just how few glacier data exist. Of the 160,000 glaciers presently in existence, only 67,000 (42%) have been inventoried to any degree (Kieffer *et al.*, 2000); and there are only a tad over 200 glaciers for which mass balance data exist *for but a single year* (Braithwaite and Zhang, 2000). When the length of record increases to *five years*, this number drops to 115; and if both winter and summer mass balances are required, the number drops to 79. Furthermore, if *ten years* of record is used as a cutoff, only 42 glaciers qualify. This lack of glacial data, in the words of Braithwaite and Zhang, highlights "one of the most important problems for mass-balance glaciology" and demonstrates the "sad fact that many glacierized regions of the world remain unsampled, or only poorly sampled," suggesting that we really know very little about the true state of most of the world's glaciers.

Recognizing the need for "more comprehensive, more homogeneous in detail and quality" glacier data (Kieffer *et al.*, 2000), we shift our attention to the few glaciers for which such data exist. During the 15th through 19th centuries, widespread and major glacier advances occurred

during a period of colder global temperature known as the Little Ice Age (Broecker, 2001; Grove, 2001). Following the peak of Little Ice Age coldness, it should come as no surprise that many records indicate widespread glacial retreat, as temperatures began to rise in the mid- to late-1800s and many glaciers returned to positions characteristic of pre-Little Ice Age times. What people may find surprising, however, is that in many instances the *rate* of glacier retreat has not increased over the past 70 years; and in some cases glacier mass balance has actually increased, all during a time when the atmosphere experienced the bulk of the increase in its CO<sub>2</sub> content.

In an analysis of Arctic glacier mass balance, for example, Dowdeswell *et al.* (1997) found that of the 18 glaciers with the longest mass balance histories, just over 80% displayed negative mass balances over their periods of record. Yet they additionally report that "almost 80% of the mass balance time series also have a *positive* trend, toward a *less negative* mass balance [our italics]." Hence, although these Arctic glaciers continue to lose mass, as they have probably done since the end of the Little Ice Age, they are losing smaller amounts each year, in the mean, which is hardly what one would expect in the face of what some incorrectly call the "unprecedented" warming of the latter part of the twentieth century.

Similar results have been reported by Braithwaite (2002), who reviewed and analyzed mass balance measurements of 246 glaciers from around the world that were made between 1946 and 1995. According to Braithwaite, "there are several regions with highly negative mass balances in agreement with a public perception of 'the glaciers are melting,' but there are also regions with positive balances." Within Europe, for example, he notes that "Alpine glaciers are generally shrinking, Scandinavian glaciers are growing, and glaciers in the Caucasus are close to equilibrium for 1980-95." And when results for the whole world are combined for this most recent period of time, Braithwaite notes that "there is no obvious common or global trend of increasing glacier melt in recent years."

As for the glacier with the longest mass balance record of all, the Storglaciaren in northern Sweden, for the first 15 years of its 50-year record it exhibited a negative mass balance of little trend. Thereafter, however, its mass balance began to trend upward, actually becoming positive over about the last decade (Braithwaite and Zhang, 2000).

So, the story glaciers have to tell us about past climate change is both far from clear and far from being adequately resolved.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/g/glaciers.php>.

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#### 4.1.2. Africa

On the floor of the U.S. Senate during debate on Senate Bill 139 back in 2004, Arizona Senator John McCain described his affection for the writings of Ernest Hemingway, especially his famous short story "The Snows of Kilimanjaro." Then, showing photos of the magnificent landmark taken in 1993 and 2000, he attributed the decline of glacial ice atop the mount during the intervening years to CO<sub>2</sub>-induced global warming, calling this attribution not only a *fact*, but a fact "that cannot be refuted by any scientist."

In subsequent debate on the same bill, New York Senator Hillary Clinton echoed Senator McCain's sentiments. Displaying a second set of photos taken from the same vantage point in 1970 and 1999 - the first depicting "a 20-foot-high glacier" and the second "only a trace of ice" - she said that in those pictures "we have evidence in the most dramatic way possible of the effects of 29 years of global warming." Nevertheless, and in spite of the *absolute certitude* with which the two senators expressed their views on the subject - which allowed for no "wiggle room" whatsoever - both of them were as *wrong* as they could possibly be.

Modern glacier recession on Kilimanjaro began around 1880, approximately the same time the planet began to recover from the several-hundred-year cold spell of the Little Ice Age. As a result, a number of people who apparently have yet to learn that *correlation does not prove causation* have vociferously declared that the ice fields retreated *because* of the rising temperatures, encouraged in this contention by a few reports in the scientific literature that

promoted the same scenario (Alverson *et al.*, 2001; Irion, 2001; Thompson *et al.*, 2002). This view of the subject, however, is "highly simplified," in the words of Molg *et al.* (2003b), who went on to demonstrate that it is also *just plain wrong*.

The trio of glaciologists began their analysis of the topic by reviewing some pertinent facts about the historic, climatic and geographic context of the long-term retreat of the Kilimanjaro ice fields. They noted, first of all, that "glacierization in East Africa is limited to three massifs close to the equator: Kilimanjaro (Tanzania, Kenya), Mount Kenya (Kenya), and Rwenzori (Zaire, Uganda)," all three of which sites experienced strong ice field recession over the past century or more. In that part of the world, however, they report "there is no evidence of a sudden change in temperature at the end of the 19th century (Hastenrath, 2001)," and that "East African long-term temperature records of the 20th century show diverse trends and do not exhibit a uniform warming signal (King'uyu *et al.*, 2000; Hay *et al.*, 2002)." Moreover, with respect to Kilimanjaro, they say that "since February 2000 an automatic weather station has operated on a horizontal glacier surface at the summit's Northern Icefield," and that "monthly mean air temperatures only vary slightly around the annual mean of  $-7.1^{\circ}\text{C}$ , and air temperatures [measured by ventilated sensors, e.g., Georges and Kaser (2002)] never rise above the freezing point," which makes it pretty difficult to understand how ice could *melt* under such conditions.

So what caused the ice fields of Kilimanjaro to recede so steadily for so many years? Citing "historical accounts of lake levels (Hastenrath, 1984; Nicholson and Yin, 2001), wind and current observations in the Indian Ocean and their relationship to East African rainfall (Hastenrath, 2001), water balance models of lakes (Nicholson and Yin, 2001), and paleolimnological data (Verschuren *et al.*, 2000)," Molg *et al.* (2003b) say "all data indicate that modern East African climate experienced an abrupt and marked drop in air humidity around 1880," and they add that the resultant "strong reduction in precipitation at the end of the 19th century is the main reason for modern glacier recession in East Africa," as it considerably reduces glacier mass balance accumulation, as has been demonstrated for the region by Kruss (1983) and Hastenrath (1984). In addition, they note that "increased incoming shortwave radiation due to decreases in cloudiness - both effects of the drier climatic conditions - plays a decisive role for glacier retreat by increasing ablation, as demonstrated for Mount Kenya and Rwenzori (Kruss and Hastenrath, 1987; Molg *et al.*, 2003a)."

In further investigating this phenomenon, Molg *et al.* (2003b) applied a radiation model to an idealized representation of the 1880 ice cap of Kilimanjaro, calculating the spatial extent and geometry of the ice cap for a number of subsequent points in time and finding that "the basic evolution in spatial distribution of ice bodies on the summit is modeled well." The model they used, which specifically addresses the unique configuration of the summit's vertical ice walls, additionally provided, in their words, "a clear indication that solar radiation is the main climatic parameter governing and maintaining ice retreat on the mountain's summit plateau in the drier climate since ca. 1880." Consequently, Molg *et al.* (2003b) concluded that "modern glacier retreat on Kilimanjaro is much more complex than simply attributable to 'global warming only'." Indeed, they say it is "a process driven by a complex combination of changes in several different climatic parameters [e.g., Kruss, 1983; Kruss and Hastenrath, 1987; Hastenrath and Kruss, 1992;

Kaser and Georges, 1997; Wagnon *et al.*, 2001; Kaser and Osmaston, 2002; Francou *et al.*, 2003; Molg *et al.*, 2003b], with humidity-related variables dominating this combination."

Also reviewing a wealth of data pertinent to the subject of African glaciers were Kaser *et al.* (2004), who similarly concluded that "changes in air humidity and atmospheric moisture content (e.g. Soden and Schroeder, 2000) seem to play an underestimated key role in tropical high-mountain climate (Broecker, 1997)." Noting that all glaciers in equatorial East Africa exhibited strong recession trends over the past century, they report that "the dominant reasons for this strong recession in modern times are reduced precipitation (Kruss, 1983; Hastenrath, 1984; Kruss and Hastenrath, 1987; Kaser and Noggler, 1996) and increased availability of shortwave radiation due to decreases in cloudiness (Kruss and Hastenrath, 1987; Molg *et al.*, 2003b)," both of which phenomena they relate to a dramatic drying of the regional atmosphere that occurred around 1880 and the ensuing dry climate that subsequently prevailed throughout the 20th century. Consequently, Kaser *et al.* likewise demonstrated that all relevant "observations and facts" clearly indicate that "climatological processes other than air temperature control the ice recession in a direct manner" on Kilimanjaro, and that "positive air temperatures have not contributed to the recession process on the summit," directly contradicting Irion (2002) and Thompson *et al.* (2002), who, in their words, see the recession of Kilimanjaro's glaciers as "a direct consequence solely of increased air temperature."

In a subsequent study of the ice fields of Kilimanjaro, Molg and Hardy (2004) derived an energy balance for the horizontal surface of the glacier that comprises the northern ice field of Kibo - the only one of the East African massif's three peaks that is presently glaciated - based on data obtained from an automated weather station. This work revealed, in their words, that "the main energy exchange at the glacier-atmosphere interface results from the terms accounting for net radiation, governed by the variation in net shortwave radiation," which is controlled by surface albedo and, thus, precipitation variability, which determines the reflective characteristics of the glacier's surface. Much less significant, according to the two researchers, is the temperature-driven turbulent exchange of sensible heat, which they say "remains considerably smaller and of little importance."

Molg and Hardy therefore went on to conclude that "modern glacier retreat on Kilimanjaro and in East Africa in general [was] initiated by a drastic reduction in precipitation at the end of the nineteenth century (Hastenrath, 1984, 2001; Kaser *et al.*, 2004)," and that reduced accumulation and increased ablation have "maintained the retreat until the present (Molg *et al.*, 2003b)." Buttressing their findings is the fact, as they report it, that "detailed analyses of glacier retreat in the global tropics uniformly reveal that changes in climate variables related to air humidity prevail in controlling the modern retreat [e.g., Kaser and Georges (1997) for the Peruvian Cordillera Blanca and Francou *et al.* (2003) for the Bolivian Cordillera Real (both South American Andes); Kruss (1983), Kruss and Hastenrath (1987), and Hastenrath (1995) for Mount Kenya (East Africa); and Molg *et al.* (2003a) for the Rwenzori massif (East Africa)]." Hence, the take-home message of their study is essentially the same as that of Kaser *et al.* (2004): "positive air temperatures have not contributed to the recession process on the summit."

Two years later in a study that describes what has actually happened to Kilimanjaro's glaciers, Cullen *et al.* (2006) report that "all ice bodies on Kilimanjaro have retreated drastically between 1912-2003," but they add that the highest glacial recession rates on Kilimanjaro "occurred in the first part of the 20th century, with the most recent retreat rates (1989-2003) *smaller than in any other interval* [our italics]." In addition, they say that no temperature trends over the period 1948-2005 have been observed at the approximate height of the Kilimanjaro glaciers, but that there has been a small decrease in the region's specific humidity over this period.

In terms of *why* glacier retreat on Kilimanjaro was so dramatic over the 20th century, the six researchers note that for the mountain's *plateau* glaciers, there is no alternative for them "other than to continuously retreat once their vertical margins are exposed to solar radiation," which appears to have happened sometime in the latter part of the 19th century. They also say, in this regard, that the "vertical wall retreat that governs the retreat of plateau glaciers is irreversible, and changes in 20th century climate have not altered their continuous demise." Consequently, the 20th-century retreat of Kilimanjaro's plateau glaciers is a long-term response to what we could call "relict climate change" that likely occurred in the late 19th century.

In the case of the mountain's *slope* glaciers, Cullen *et al.* say that their rapid recession in the first part of the 20th century clearly shows they "were drastically out of equilibrium," which they take as evidence that the glaciers "were responding to a large *prior* [our italics] shift in climate." In addition, they report that "no footprint of multidecadal changes in areal extent of slope glaciers to fluctuations in 20th century climate is observed, but their ongoing demise does suggest they are still out of equilibrium," and in this regard they add that their continuing but decelerating demise could be helped along by the continuous slow decline in the air's specific humidity. Consequently, and in light of all the facts they present and the analyses they and others have conducted over many years, Cullen *et al.* confidently conclude that the glaciers of Kilimanjaro "are merely remnants of a past climate rather than sensitive indicators of 20th century climate change," the adamant prior statements of U.S. Senators McCain and Clinton notwithstanding.

Continuing on the same theme, Mote and Kaser (2007) and Duane *et al.* (2008) additionally reject the temperature-induced decline hypothesis for Kilimanjaro, with Duane *et al.* concluding that "the reasons for the rapid decline in Kilimanjaro's glaciers are not primarily due to increased air temperatures, but a lack of precipitation," and Mote and Kaser reporting that "warming fails *spectacularly* [our italics] to explain the behavior of the glaciers and plateau ice on Africa's Kilimanjaro massif .. and to a lesser extent other tropical glaciers." Clearly, the misguided rushes to judgment that have elevated Kilimanjaro's predicted demise by CO<sub>2</sub>-induced global warming to iconic status should give everyone pause to more carefully evaluate the evidence, or lack thereof, for many similar claims related to the ongoing rise in the air's CO<sub>2</sub> content.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/a/africagla.php>.

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### 4.1.3. Antarctica

Sometime in early November of 2001, a large iceberg separated from West Antarctica's Pine Island Glacier. This event was of great interest to scientists, because the Pine Island Glacier is currently the fastest moving glacier in Antarctica and the continent's largest discharger of ice, which facts have led some to speculate that this event could herald the "beginning of the end" of the West Antarctic Ice Sheet. A number of scientific studies, however, suggest otherwise.

Rignot (1998) employed satellite radar measurements of the grounding line of Pine Island Glacier from 1992 to 1996 to determine whether or not it was advancing or retreating. The data indicated a retreat rate of  $1.2 \pm 0.3$  kilometers per year over the four-year period of the study. Because this period was so short, however, Rignot says that the questions the study raises concerning the long-term stability of the West Antarctic Ice Sheet "cannot be answered at present."

In a subsequent study, Stenoien and Bentley (2000) mapped the catchment region of Pine Island Glacier using radar altimetry and synthetic aperture radar interferometry, after which they used the data to develop a velocity map that revealed a system of tributaries that channel ice from the catchment area into the fast-flowing glacier. By combining these velocity data with information on ice thickness and snow accumulation rates, they were ultimately able to calculate an approximate mass balance for the glacier; and within an uncertainty of approximately 30%, their results suggested that the mass balance of the catchment region was not significantly different from zero.

In yet another study of Pine Island Glacier, Shepherd *et al.* (2001) used satellite altimetry and interferometry to determine the rate of change of thickness of its entire drainage basin between 1992 and 1999, determining that the grounded glacier thinned by up to 1.6 meters per year over this period. In commenting on this result, they note that "the thinning cannot be explained by short-term variability in accumulation and must result from glacier dynamics." And since glacier dynamics are typically driven by phenomena operating on time scales of hundreds to thousands of years, this observation would argue against 20th century warming being the cause of the thinning. Shepherd *et al.* additionally say they could "detect no change in the rate of ice thinning across the glacier over [the] 7-year period," which also suggests that a long-term phenomenon of considerable inertia must be at work in this particular situation.

But what if the rate of glacier thinning, which *sounds* pretty dramatic, continues unabated? Shepherd *et al.* state that "if the trunk continues to lose mass at the present rate it will be

entirely afloat within 600 years." And if that happens? They say they "estimate the net contribution to eustatic sea level to be 6 mm," which means that for each century of the foreseeable future, we could expect global mean sea level to rise by approximately one millimeter ... or about the thickness of a common paper clip.

Turning to other glaciers, Hall and Denton (2002) mapped the distribution and elevation of surficial deposits along the southern Scott Coast of Antarctica in the vicinity of the Wilson Piedmont Glacier, which runs parallel to the coast of the western Ross Sea from McMurdo Sound north to Granite Harbor. The chronology of the raised beaches was determined from more than 60  $^{14}\text{C}$  dates of organic materials they had previously collected from hand-dug excavations (Hall and Denton, 1999). They also evaluated more recent changes in snow and ice cover based on aerial photography and observations carried out since the late 1950s. So what did they find?

Near the end of the Medieval Warm Period - "as late as 890  $^{14}\text{C}$  yr BP," as Hall and Denton put it - "the Wilson Piedmont Glacier was still less extensive than it is now." Hence, they rightly conclude that the glacier had to have advanced within the last several hundred years, although they note that its eastern margin has retreated within the last 50 years. In addition, they report a number of similar observations by other investigators. Citing evidence collected by Baroni and Orombelli (1994a), they note there was "an advance of at least one kilometer of the Hell's Gate Ice Shelf ... within the past few hundred years." And they report that Baroni and Orombelli (1994b) "documented post-fourteenth century advance of a glacier near Edmonson's Point." Summarizing these and other findings, they conclude that evidence from the Ross Sea area suggests "late-Holocene climatic deterioration and glacial advance (within the past few hundred years) and twentieth century retreat."

In speaking of the significance of the "recent advance of the Wilson Piedmont Glacier," Hall and Denton report that it "overlaps in time with the readvance phase known in the Alps [of Europe] as the 'Little Ice Age'," which they further note "has been documented in glacial records as far afield as the Southern Alps of New Zealand (Wardle, 1973; Black, 2001), the temperate land mass closest to the Ross Sea region." They further note that "Kreutz *et al.* (1997) interpreted the Siple Dome [Antarctica] glaciochemical record as indicating enhanced atmospheric circulation intensity at AD ~1400, similar to that in Greenland during the 'Little Ice Age' (O'Brien *et al.*, 1995)." In addition, they report that "farther north, glaciers in the South Shetland Islands adjacent to the Antarctic Peninsula underwent a late-Holocene advance, which has been correlated with the 'Little Ice Age' (Birkenmajer, 1981; Clapperton and Sugden, 1988; Martinex de Pison *et al.*, 1996; Bjoreck *et al.*, 1996)."

In summarizing the results of their work, Hall and Denton say "the Wilson Piedmont Glacier appears to have undergone advance at approximately the same time as the main phase of the 'Little Ice Age', followed by twentieth-century retreat at some localities along the Scott Coast." This result and the others they cite make it very clear that glacial activity on Antarctica has followed the pattern of millennial-scale variability that is evident elsewhere in the world: recession to positions during the Medieval Warm Period that have not yet been reached in our

day, followed by significant advances during the intervening Little Ice Age, which is quite a different story from what the infamous "hockeystick" temperature history suggests, when temperatures of the past few decades supposedly rose to levels unprecedented in the past millennium.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/a/antarcticagla.php>.

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#### 4.1.4. Arctic

Computer simulations of global climate change have long indicated the world's polar regions should show the first and severest signs of CO<sub>2</sub>-induced global warming. If the models are correct, these signs should be especially evident in the second half of the 20th century, when approximately two-thirds of the modern-era rise in atmospheric CO<sub>2</sub> occurred and earth's temperature supposedly rose to a level unprecedented in the entire past millennium. In this subsection, we examine historic trends in Arctic glacier behavior to determine the credibility of current climate models with respect to their polar predictions.

In a review of "the most current and comprehensive research of Holocene glaciation," along the northernmost Gulf of Alaska between the Kenai Peninsula and Yakutat Bay, Calkin *et al.* (2001) report there were several periods of glacial advance and retreat over the past 7000 years. Over the most recent of those seven millennia, there was a general retreat during the Medieval Warm Period that lasted for "at least a few centuries prior to A.D. 1200." Then came three major intervals of Little Ice Age glacial advance: the early 15th century, the middle 17th century, and the last half of the 19th century. During these very cold periods, glacier equilibrium-line altitudes were depressed from 150 to 200 m below present values, as Alaskan glaciers "reached their Holocene maximum extensions."

Subsequent to this time, as the planet emerged from the depths of the Little Ice Age, the mass balance records of the 18 Arctic glaciers with the longest observational histories were studied by Dowdeswell *et al.* (1997). Their analysis showed that over 80% of the glaciers displayed negative mass balances over the periods of their observation, as would logically be expected for glaciers emerging from the coldest part of the past millennium. Nevertheless, the scientists report that "ice-core records from the Canadian High Arctic islands indicate that the generally negative glacier mass balances observed over the past 50 years [when the vast majority of the CO<sub>2</sub> resulting from human activities entered the atmosphere] have probably been typical of

Arctic glaciers *since the end of the Little Ice Age* [our italics]," when the magnitude of anthropogenic CO<sub>2</sub> emissions was a whole lot less than it has been from 1950 onward.

These observations suggest that Arctic glaciers are not experiencing *any* adverse effects of anthropogenic CO<sub>2</sub> emissions. In fact, Dowdeswell *et al.* say "there is no compelling indication of increasingly negative balance conditions which might, *a priori*, be expected from anthropogenically induced global warming." Quite to the contrary, they report that "almost 80% of the mass balance time series also have a *positive* trend, toward a *less* negative mass balance [our italics]." Hence, although most Arctic glaciers continue to lose mass, as they have probably done since the end of the Little Ice Age, they are losing smaller amounts each year, in the mean, which is hardly what one would expect in the face of what climate alarmists say is happening to earth's climate.

Additional evidence that the Arctic's glaciers are not responding to human-induced warming comes from the studies of Zeeberg and Forman (2001) and Mackintosh *et al.* (2002), who indicate there has been an *expansion* of glaciers in the European Arctic over the past few decades.

Zeeberg and Forman analyzed 20th-century changes in glacier terminus positions on north Novaya Zemlya -- a Russian island located between the Barents and Kara Seas in the Arctic Ocean -- providing a quantitative assessment of the effects of temperature and precipitation on glacial mass balance. The results of their study showed a significant and accelerated post-Little Ice Age glacial retreat in the first and second decades of the 20th century. By 1952, however, the region's glaciers had experienced between 75 to 100% of their net 20th-century retreat; and during the next 50 years, the recession of over half of the glaciers stopped, while many tidewater glaciers actually began to advance.

These glacial stabilizations and advances were attributed by the authors to observed increases in precipitation and/or decreases in temperature. For the four decades since 1961, for example, weather stations on Novaya Zemlya show summer temperatures were 0.3 to 0.5°C colder than they were over the prior 40 years, while winter temperatures were 2.3 to 2.8°C colder than they were over that earlier period. These observations, the authors say, are "counter to warming of the Eurasian Arctic predicted for the twenty-first century by climate models, particularly for the winter season"

Other glacier observations that run counter to climate model predictions are discussed by Mackintosh *et al.* (2002), who concentrated on the 300-year history of the Solheimajokull outlet glacier on the southern coast of Iceland. In 1705, this glacier had a length of about 14.8 km; and by 1740 it had grown to 15.2 km in length. Thereafter, it began to retreat, reaching a minimum length of 13.2 km in 1783. Rebounding rapidly, however, the glacier returned to its 1705 position by 1794; and by 1820 it equaled its 1740 length. This maximum length was maintained for the next half-century, after which the glacier began a slow retreat that continued to about 1932, when its length was approximately 14.75 km. Then it wasted away

more rapidly, reaching a second minimum-length value of approximately 13.8 km about 1970, whereupon it began to *rapidly expand*, growing to 14.3 km by 1995.

The current position of the outlet glacier terminus is by no means unusual. In fact, it is about midway between its maximum and minimum positions of the past three centuries. It is also interesting to note that the glacier has been *growing* in length since about 1970. In addition, Mackintosh *et al.* report that "the recent advance (1970-1995) resulted from a combination of cooling and enhancement of precipitation."

In another study of the Arctic, Humlum *et al.* (2005) evaluated climate dynamics and their respective impacts on high-latitude glaciers for the Archipelago of Svalbard, focusing on Spitsbergen (the Archipelago's main island) and the Longyearbreen glacier located in its relatively dry central region at 78°13'N latitude. In reviewing what was already known about the region, Humlum *et al.* report that "a marked warming around 1920 changed the mean annual air temperature (MAAT) at sea level within only 5 years from about -9.5°C to -4.0°C," which change, in their words, "represents the most pronounced increase in MAAT documented anywhere in the world during the instrumental period." Then, they report that "from 1957 to 1968, MAAT dropped about 4°C, followed by a more gradual increase towards the end of the twentieth century."

With respect to the Longyearbreen glacier, their own work reveals it "has increased in length from about 3 km to its present size of about 5 km during the last c. 1100 years," and they say that "the meteorological setting of *non-surg*ing [our italics] Longyearbreen suggest this example of late-Holocene glacier growth represents a widespread phenomenon in Svalbard and in adjoining Arctic regions," which they describe as a "development towards cooler conditions in the Arctic" that "may explain why the Little Ice Age glacier advance in Svalbard usually represents the Holocene maximum glacier extension."

Climate change in Svalbard over the 20th century was a real rollercoaster ride, with temperatures rising more rapidly in the early 1920s than has been documented anywhere else before or since, only to be followed by a nearly equivalent temperature drop four decades later, both of which climatic transitions were totally out of line with what climate models suggest should have occurred. In addition, the current location of the terminus of the Longyearbreen glacier suggests that, even now, Svalbard and "adjoining Arctic regions" are still experiencing some of the lowest temperatures of the entire Holocene or current interglacial, and at a time when atmospheric CO<sub>2</sub> concentrations are higher than they have likely been for *millions* of years, both of which observations are also at odds with what climate alarmists claim about the strong warming power of atmospheric CO<sub>2</sub> enrichment. Hence, there is little reason to put much faith in their claims, or to get too excited if the Arctic *were* to warm a bit ... or even *substantially* and at a *rapid rate*. It's done so before, and it will likely do so again. In fact, it's only to be *expected*, seeing the region has a long way to go to recover from some of the coldest temperatures of the entire interglacial.

Lastly, Bradwell *et al.* (2006) examined the link between late Holocene fluctuations of Lambatungnajokull (an outlet glacier of the Vatnajokull ice cap of southeast Iceland) and variations in climate, using geomorphological evidence to reconstruct patterns of glacier fluctuations and using lichenometry and tephrostratigraphy to date glacial landforms created by the glacier over the past four centuries. Results indicated that "there is a particularly close correspondence between summer air temperature and the rate of ice-front recession of Lambatungnajokull during periods of overall retreat," and that "between 1930 and 1950 this relationship is striking." They also report that "ice-front recession was greatest during the 1930s and 1940s, when retreat averaged 20 m per year." Thereafter, they say the retreat "slowed in the 1960s," and they report "there has been little overall retreat since the 1980s."

The researchers also report that "the 20th-century record of reconstructed glacier-front fluctuations at Lambatungnajokull compares well with those of other similar-sized, non-surging, outlets of southern Vatnajokull," including Skaftafellsjokull, Fjallsjokull, Skalafellsjokull and Flaajokull. In fact, they find that "the pattern of glacier fluctuations of Lambatungnajokull over the past 200 years reflects the climatic changes that have occurred in southeast Iceland and the wider region."

Bradwell *et al.*'s findings suggest that 20th-century summer air temperature in southeast Iceland *and the wider region* peaked in the 1930s and 1940s, and was followed by a cooling that persisted through the end of the century. This thermal behavior is about as different as one could imagine from the *claim* that the warming of the globe over the last two decades of the 20th century was *unprecedented over the past two millennia*; and especially is this so for a high-northern-latitude region, where climate alarmists claim CO<sub>2</sub>-induced global warming should be *earliest and most strongly expressed*.

Apparently, Iceland and many other high-latitude regions "just don't get it." Or is it the *climate alarmists* that suffer this malady, failing to realize (or, worse yet, *refusing to acknowledge*) that many key parts of the world that are supposedly super-sensitive to greenhouse-gas forcing are just not responding to anthropogenic CO<sub>2</sub> emissions the way they say they should?

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/a/arcticgla.php>.

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#### 4.1.5. Europe

Joerin *et al.* (2006) examined glacier recessions in the Swiss Alps over the past ten thousand years based on radiocarbon-derived ages of materials found in proglacial fluvial sediments of subglacial origin, focusing on subfossil remains of wood and peat. Combining their results with earlier data of a similar nature, they then constructed a master chronology of Swiss glacier fluctuations over the course of the Holocene. So what did they find?

First of all, Joerin *et al.* report discovering that "alpine glacier recessions occurred at least 12 times during the Holocene," once again demonstrating the reality of the millennial-scale oscillation of climate that has reverberated throughout glacial and interglacial periods alike as far back in time as scientists have searched for the phenomenon. As a result of this finding, it is clear that 20th-century global warming was *not unusual*. It was merely the latest example of what has been the *norm* throughout hundreds of thousands of years.

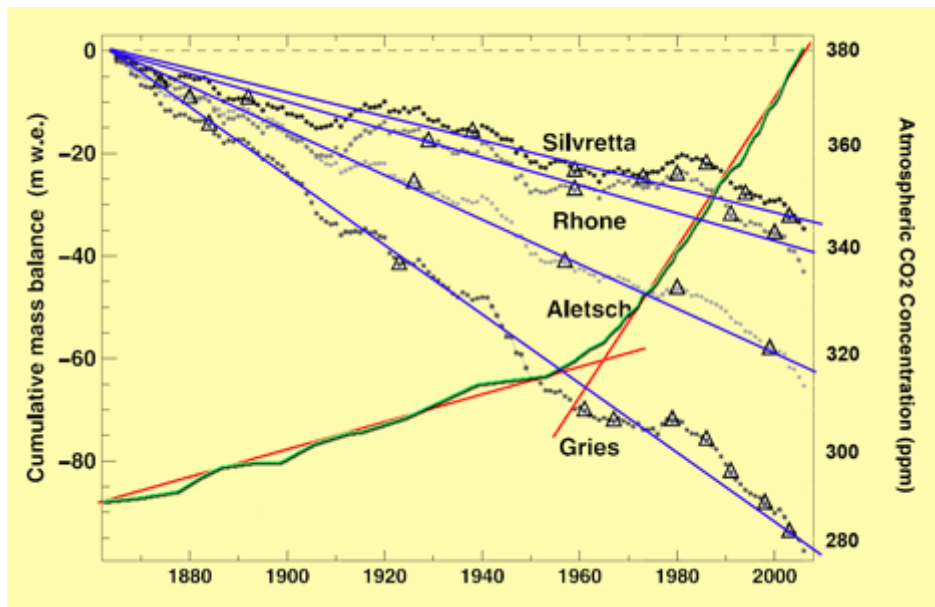
Second, they determined that glacier recessions have been decreasing in frequency since approximately 7000 years ago, and especially since 3200 years ago, "culminating in the maximum glacier extent of the 'Little Ice Age'." Consequently, the significant warming of the 20th century cannot be considered strange, since it represents a climatic rebounding from the *coldest period of the current interglacial*, which interglacial just happens to be the coldest of the last *five* interglacials (Petit *et al.*, 1999). And when the earth has been *that* cold for a few centuries, it is *not unnatural* to expect that, once started, warming would be rather significant.

Third, the last of the major glacier recessions in the Swiss Alps occurred between about 1400 and 1200 years ago, according to Joerin *et al.*'s data, but between 1200 and 800 years ago, according to the data of Holzhauser *et al.* (2005) for the Great Aletsch Glacier. Of this discrepancy, Joerin *et al.* say that given the uncertainty of the radiocarbon dates, the two records need not be considered inconsistent with each other. What is more, their presentation of the Great Aletsch Glacier data indicates that the glacier's length at about AD 1000 - when



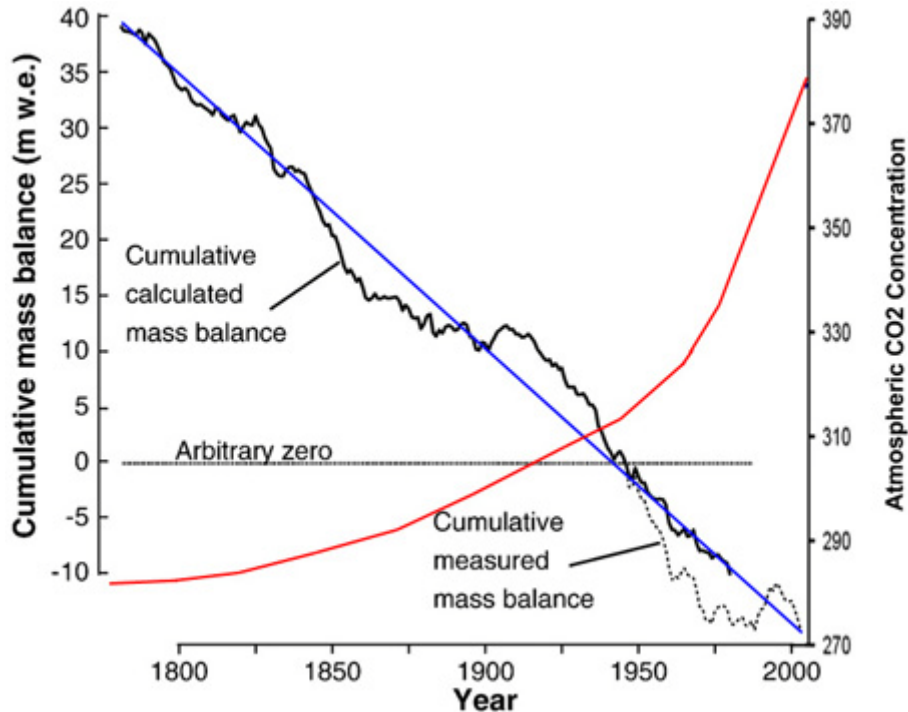
there was fully 100 ppm *less* CO<sub>2</sub> in the air than there is today - was just slightly less than its length in 2002, suggesting that the peak temperature of the Medieval Warm Period likely was slightly higher than the peak temperature of the 20th century. Consequently, 20th-century warming has likely *not* been **unprecedented** over the past millennium.

Also in the Swiss Alps, Huss *et al.* (2008) examined various ice and meteorological measurements made between 1865 and 2006 in an effort to compute the yearly mass balances (positive for growth, negative for shrinkage) of four glaciers. The results of their computations can be seen in the figure below. The most obvious conclusion to be drawn from these data -- and the conclusion climate alarmists are quick to promote -- is the fact that each of the four glaciers has indeed decreased in size. But even more important than this observation is the fact that the *rate of shrinkage has not accelerated over time*, as evidenced by the long-term trend lines we have fit to the data (solid blue lines). What is more, there is no compelling evidence that this 14-decade-long glacial decline has had anything at all to do with the air's CO<sub>2</sub> content.



Consider, for example, the changes in atmospheric CO<sub>2</sub> concentration experienced over the same time period (solid green line). If we compute the mean rate-of-rise of the air's CO<sub>2</sub> content from the start of the record to about 1950, and from about 1970 to 2006 (solid red lines), we see that between 1950 and 1970 the rate-of-rise of the atmosphere's CO<sub>2</sub> concentration increased by *more than five-fold*, yet there were no related increases in the long-term mass balance trends of the four glaciers. Hence, it is clear that the ice loss history of the glaciers was not unduly influenced by the huge increase in the rate-of-rise of the air's CO<sub>2</sub> content that occurred between 1950 and 1970, and that their rate of shrinkage was also not materially altered by what climate alarmists call the *unprecedented warming* of the last few decades, which they claim was greater than any other warming of the last one to two thousand years.

Moving to northern Europe, Linderholm et al. (2007) examined "the world's longest ongoing continuous mass-balance record" of "Storglaciaren in northernmost Sweden," which they report "is generally well correlated to glaciers included in the regional mass balance program (Holmlund and Jansson, 1999), suggesting that it represents northern Swedish glaciers." The results of their work are depicted in the figure below, where we have also plotted the contemporaneous history of the atmosphere's CO<sub>2</sub> concentration.



The cumulative reconstructed net mass balance (bn) history of Sweden's Storglaciaren (to which we have added the fit-by-eye descending linear relationship), in blue, and the history of the atmosphere's CO<sub>2</sub> concentration, in red. Adapted from Linderholm et al. (2007).

In viewing the figure, it should be evident to all that the historical increase in the air's CO<sub>2</sub> content has had absolutely *no discernable impact whatsoever* on the net mass balance history of Sweden's Storglaciaren over the past two and a quarter centuries. Whereas the mean rate-of-rise of the air's CO<sub>2</sub> concentration over the last half-century of Storglaciaren mass balance data is fully *fifteen times greater* than what it was over the first half-century of mass balance data (and some *forty times greater* if the first and last *quarter-centuries* are considered), there has been no sign of any change in the long-term trend of Storglaciaren's net mass balance, which just keeps doing its own thing, seemingly *totally oblivious* to the concurrent *huge acceleration* in the rate-of-rise of the atmosphere's CO<sub>2</sub> concentration.

In addition to the results of the two papers referenced above, other studies have shown that not all European glaciers are experiencing a current retreat. A typical example is described by D'Orefice et al. (2000), who assembled and analyzed a wealth of historical data to derive a history of post-LIA shrinkage of the surface area of the southernmost glacier of Europe,

Ghiacciaio del Calderone. From the first available information on the glacier's surface area in 1794, there was a very slow ice wastage that lasted until 1884, whereupon the glacier began to experience a more rapid area reduction that continued, with some irregularities, to 1990, resulting in a loss of just over half the glacier's LIA surface area.

Not all European glaciers, however, have experienced continuous declines since the end of the Little Ice Age. Hormes *et al.* (2001), for example, report that glaciers in the Central Swiss Alps experienced two periods of *readvancement*, one around 1920 and another as recent as 1980. In addition, Braithwaite (2002) reports that for the period 1980-1995, "Scandinavian glaciers [have been] growing, and glaciers in the Caucasus are close to equilibrium," while "there is no obvious common or global trend of increasing glacier melt."

Fifty years of mass balance data from the storied Storglaciaren of northwestern Sweden also demonstrate a trend reversal in the late 20th Century. According to Braithwaite and Zhang (2000), there has been a significant upward trend in the mass balance of this glacier over the past 30-40 years, and it has been in a state of mass *accumulation* for at least the past decade. Additional evidence for post-LIA glacial expansion is provided by the history of the Solheimajokull outlet glacier on the southern coast of Iceland. In a review of its length over the past 300 years, Mackintosh *et al.* (2002) report a post-LIA minimum of 13.8 km in 1970, whereupon the glacier began to expand, growing to a length of about 14.3 km by 1995. The minimum length of 13.8 km observed in 1970 also did not eclipse an earlier minimum in which the glacier had decreased from a 300-year maximum length of 15.2 km in 1740 to a 300-year minimum of 13.2 km in 1783.

Still more recent glacial advances have been reported in Norway. According to Chin *et al.* (2005), glacial recession in Norway was most strongly expressed in "the middle of the 20th century," ending during the late 1950s to early 1960s." Then, "after some years with more or less stationary glacier front positions, [the glaciers] began to advance, accelerating in the late 1980s." Around 2000, a portion of the glaciers began to slow, while some even ceased moving; but they say that "most of the larger outlets with longer reaction times are continuing to advance." In fact, Chin *et al.* report that "the distances regained and the duration of this recent advance episode are both far greater than any previous readvance since the Little Ice Age maximum, making the recent resurgence a significant event." Mass balance data reveal much the same thing, "especially since 1988" and "at all [western] maritime glaciers in both southern and northern Norway," where "frequent above-average winter balances are a main cause of the positive net balances at the maritime glaciers during the last few decades."

The advances and retreats of glaciers are often interpreted as signs of climate change; and teams of glaciologists have been working for years to provide an assessment of the state of the world's many glaciers to help decipher global climate trends. Although this effort has only scratched the surface of what must ultimately be done, some climate alarmists have already concluded there has been a massive and widespread retreat of glaciers over the past century, which they predict will only intensify under continued CO<sub>2</sub>-induced global warming. In considering the results of the studies summarized above, however, it would appear that several

European glaciers are marching to the beat of a different drummer: holding their own -- or actually *advancing* -- over the past quarter century, a period of time in which the climate alarmists claim the earth has warmed to its highest temperature of the past thousand years.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/e/europegla.php>.

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#### 4.1.6. North America

Does the history of North American glacial activity support the claim that anthropogenic CO<sub>2</sub> emissions drove temperatures to new and unprecedented heights near the end of the 20th century? We here review some studies of North American glaciers that speak to this issue.

Dowdeswell *et al.* (1997) analyzed the mass balance histories of the 18 Arctic glaciers that have the longest observational records, finding that just over 80% of them displayed negative mass balances over the last half of the 20th century. However, they note that "ice-core records from the Canadian High Arctic islands indicate that the generally negative glacier mass balances observed over the past 50 years have probably been typical of Arctic glaciers since the end of the Little Ice Age." Also, they emphatically state "there is no compelling indication of increasingly negative balance conditions which might, *a priori*, be expected from anthropogenically induced global warming." Quite to the contrary, they report that "almost 80% of the mass balance time series also have a positive trend, toward a less negative mass balance." Hence, although most of these High Arctic Canadian glaciers continue to lose mass, as they have probably done since the end of the Little Ice Age, they are losing smaller amounts each year, in the mean, which is not what one would expect in the face of rapidly rising atmospheric CO<sub>2</sub> concentrations if they truly drive global warming as dramatically as climate-alarmists say they do.

Also reporting from Canada, Clague *et al.* (2004) documented glacier and vegetation changes at high elevations in the upper Bowser River basin in the northern Coast Mountains of British Columbia, based on studies of the distributions of glacial moraines and trimlines, tree-ring data, cores from two small lakes that were sampled for a variety of analyses (magnetic susceptibility, pollen, diatoms, chironomids, carbon and nitrogen content, <sup>210</sup>Pb, <sup>137</sup>Cs, <sup>14</sup>C), similar analyses of materials obtained from pits and cores from a nearby fen, and by accelerator mass spectrometry radiocarbon dating of plant fossils, including wood fragments, tree bark, twigs and conifer needles and cones. All this evidence suggested a glacial advance that began about 3000 years ago and may have lasted for hundreds of years, which would have placed it within the unnamed cold period that preceded the Roman Warm Period. There was also evidence for a second minor phase of activity that began about 1300 years ago but was of short duration, which would have placed it within the Dark Ages Cold Period. Finally, the third and most extensive Neoglacial interval began shortly after AD 1200, following the Medieval Warm Period, and ended in the late 1800s, which was, of course, the Little Ice Age, during which time Clague *et al.* say that "glaciers achieved their greatest extent of the past 3000 years and probably the last 10,000 years."

These data clearly depict the regular alternation between non-CO<sub>2</sub>-forced multi-century cold and warm periods that is the trademark of the millennial-scale oscillation of climate that reverberates throughout glacial and interglacial periods alike. That a significant, but by no

means unprecedented, warming followed the most recent cold phase of this cycle is in no way unusual, particularly since the Little Ice Age was likely *the coldest period of the last 10,000 years*. The significant warming of the 20th century would have occurred within the same timeframe and been just as strong even if the atmosphere's CO<sub>2</sub> content had remained constant at pre-industrial levels; it was simply the next scheduled phase of this ever-recurring natural climatic oscillation.

In a study based in Alaska, Calkin *et al.* (2001) reviewed the most current and comprehensive research of Holocene glaciation along the northernmost portion of the Gulf of Alaska between the Kenai Peninsula and Yakutat Bay, where several periods of glacial advance and retreat were noted during the past 7000 years. Over the latter part of this record, there was a general glacial retreat during the Medieval Warm Period that lasted for a few centuries prior to A.D. 1200, after which there were three major intervals of Little Ice Age glacial advance: the early 15th century, the middle 17th century, and the last half of the 19th century. During these latter time periods, glacier equilibrium line altitudes were depressed from 150 to 200 m below present values as Alaskan glaciers also "reached their Holocene maximum extensions." Hence, it is only to be expected that Alaska's temperatures would rise significantly and its glaciers would lose mass at significant rates during the planet's natural recovery from *the coldest period of the current interglacial*.

In another study from Alaska, Wiles *et al.* (2004) derived a composite Glacier Expansion Index (GEI) for the state based on "dendrochronologically-derived calendar dates from forests overrun by advancing ice and age estimates of moraines using tree-rings and lichens" for three climatically-distinct regions -- the Arctic Brooks Range, the southern transitional interior straddled by the Wrangell and St. Elias mountain ranges, and the Kenai, Chugach and St. Elias coastal ranges -- after which they compared this history of glacial activity with "the <sup>14</sup>C record preserved in tree rings corrected for marine and terrestrial reservoir effects as a proxy for solar variability" and with the history of the Pacific Decadal Oscillation (PDO) derived by Cook (2002). As a result of their efforts, Wiles *et al.* discovered that "Alaska shows ice expansions approximately every 200 years, compatible with a solar mode of variability," specifically, the de Vries 208-year solar cycle; and by merging this cycle with the cyclical behavior of the PDO, they obtained a dual-parameter forcing function that was even better correlated with the Alaskan composite GEI, with major glacial advances clearly associated with the Sporer, Maunder and Dalton solar minima.

In describing the rationale for their study, Wiles *et al.* said that "increased understanding of solar variability and its climatic impacts is critical for separating anthropogenic from natural forcing and for predicting anticipated temperature change for future centuries." In this regard, it is most interesting that they made *no mention* of possible CO<sub>2</sub>-induced global warming in discussing their results, presumably because *there was no need to do so*. Alaskan glacial activity, which in their words "has been shown to be primarily a record of summer temperature change (Barclay *et al.*, 1999)," appears to be sufficiently well described within the context of centennial (solar) and decadal (PDO) variability superimposed upon the millennial-scale (non-

CO<sub>2</sub>-forced) variability that produces longer-lasting Medieval Warm Period and Little Ice Age conditions.

Dropping down into the conterminous United States, Pederson *et al.* (2004) used tree-ring reconstructions of North Pacific surface temperature anomalies and summer drought as proxies for winter glacial accumulation and summer ablation, respectively, to create a 300-year history of regional glacial Mass Balance Potential (MBP), which they compared with historic retreats and advances of Glacier Park's extensively-studied Jackson and Agassiz glaciers. What they found was most interesting. As they describe it, "the maximum glacial advance of the Little Ice Age coincides with a sustained period of positive MBP that began in the mid-1770s and was interrupted by only one brief ablation phase (~1790s) prior to the 1830s," after which they report that "the mid-19th century retreat of the Jackson and Agassiz glaciers then coincides with a period marked by strong negative MBP." From about 1850 onward, for example, they note that "Carrara and McGimsey (1981) indicate a modest retreat (~3-14 m/yr) for both glaciers until approximately 1917." At that point, they report that "the MBP shifts to an extreme negative phase that persists for ~25 yr," during which period the glaciers retreated "at rates of greater than 100 m/yr."

Continuing with their history, Pederson *et al.* report that "from the mid-1940s through the 1970s retreat rates slowed substantially, and several modest advances were documented as the North Pacific transitioned to a cool phase [and] relatively mild summer conditions also prevailed." Thereafter, however, from the late 1970s through the 1990s, they say that "instrumental records indicate a shift in the PDO back to warmer conditions resulting in continuous, moderate retreat of the Jackson and Agassiz glaciers."

The first illuminating aspect of this glacial history is that the post-Little Ice Age retreat of the Jackson and Agassiz glaciers began just after 1830, in harmony with the findings of a number of other studies from various parts of the world (Vincent and Vallon, 1997; Vincent, 2001, 2002; Moore *et al.*, 2002; Yoo and D'Odorico, 2002; Gonzalez-Rouco *et al.* 2003; Jomelli and Pech, 2004), *including the entire Northern Hemisphere* (Briffa and Osborn, 2002; Esper *et al.*, 2002), which finding stands in stark contrast to what is suggested by the IPCC-endorsed "hockeystick" temperature history of Mann *et al.* (1998, 1999), which does not portray *any* Northern Hemispheric warming until around 1910. The second illuminating aspect of the glacial record is that the vast bulk of the glacial retreat in Glacier National Park occurred between 1830 and 1942, over which time the air's CO<sub>2</sub> concentration rose by only 27 ppm, which is less than a third of the total CO<sub>2</sub> increase experienced since the start of glacial recession. Then, from the mid-1940s through the 1970s, when the air's CO<sub>2</sub> concentration rose by another 27 ppm, Pederson *et al.* report that "retreat rates slowed substantially, and several modest advances were documented."

It is illuminating to note, in this regard, that the first 27 ppm increase in atmospheric CO<sub>2</sub> concentration coincided with the great preponderance of glacial retreat experienced since the start of the warming that marked the "beginning of the end" of the Little Ice Age, but that the

next 27 ppm increase in the air's CO<sub>2</sub> concentration was accompanied by little if any additional glacial retreat, when, of course, there was little if any additional warming.

Clearly, and contrary to the strident claims of climate alarmists, something other than the historic rise in the air's CO<sub>2</sub> content has been responsible for the disappearing ice fields of Glacier National Park. It should also be clear to all that the historical behavior of North America's glaciers provides no evidence whatsoever for unprecedented or unnatural CO<sub>2</sub>-induced global warming over any part of the 20th century.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/n/northamgla.php>.

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#### 4.1.7. South America

The results of studies of past glacial activity in South America add to the accumulating evidence from around the world that suggests that the recent retreat of mountain glaciers is neither *unprecedented nor CO<sub>2</sub>-induced*, but rather the *expected* result of the *natural* recovery of the earth from the *global* chill of the Little Ice Age, which latter period the world's climate alarmists strive to convince people was but a *regional* phenomenon confined to lands surrounding the North Atlantic Ocean.

Harrison and Winchester (2000) used dendrochronology, lichenometry and aerial photography to date 19th- and 20th-century fluctuations of the Arco, Colonia and Arenales glaciers on the eastern side of the Hielo Patagonico Norte in southern Chile. This work revealed that these glaciers, plus four others on the western side of the ice field, began to retreat, in the words of

the two researchers, "from their Little Ice Age maximum positions" somewhere between 1850 and 1880, *well before the air's CO<sub>2</sub> content began to rise at a significant rate*. They also note that the trend continued "through the first half of the 20th century with various still-stands and oscillations between 1925 and 1960 ... with retreat increasing since the 1960s," just as has been observed at many sites in the Northern Hemisphere. Consequently, it is becoming ever more clear that even as far away from the lands that surround the North Atlantic Ocean as *southern Chile*, the Little Ice Age is evident in a variety of proxy climate records.

Still, however, the question remains: what caused the global warming that led to the Little Ice Age's demise throughout the world?

The likely answer to this question is provided by Glasser *et al.* (2004), who describe a large body of evidence related to glacier fluctuations in the two major ice fields of Patagonia: the Hielo Patagonico Norte and the Hielo Patagonico Sur. This evidence indicates that the most recent glacial advances in Patagonia occurred during the Little Ice Age, out of which serious cold spell the earth has been gradually emerging for the past century and a half, causing many glaciers to retreat. Prior to the Little Ice Age, however, their data indicate an interval of higher temperatures known as the Medieval Warm Period, when glaciers also decreased in size and extent; and this warm interlude was in turn preceded by a still earlier era of pronounced glacial activity that is designated the Dark Ages Cold Period, which was also preceded by a period of higher temperatures and retreating glaciers that is denoted the Roman Warm Period.

Prior to the Roman Warm Period, Glasser *et al.*'s presentation of the pertinent evidence suggests there was another period of significant glacial advance that also lasted several hundred years, which was preceded by a several-century interval when glaciers once again lost ground, which was preceded by yet another multi-century period of glacial advance, which was preceded by yet another long interval of glacier retrenchment, which was preceded by still another *full cycle* of such temperature-related glacial activity, which brings us all the way back to sometime between 6000 and 5000 <sup>14</sup>C years before present (BP).

Glasser *et al.* additionally cited the works of a number of other scientists that reveal a similar pattern of cyclical glacial activity over the preceding millennia in several other locations. Immediately to the east of the Hielo Patagonico Sur in the Rio Guanaco region of the Precordillera, for example, they report that Wenzens (1999) detected five distinct periods of glacial advancement: "4500-4200, 3600-3300, 2300-2000, 1300-1000 <sup>14</sup>C years BP and AD 1600-1850." With respect to the glacial advancements that occurred during the cold interval that preceded the Roman Warm Period, they say they constitute "part of a body of evidence for global climatic change around this time (e.g., Grosjean *et al.*, 1998; Wasson and Claussen, 2002) which coincides with an abrupt decrease in solar activity," and they say that this observation was what "led van Geel *et al.* (2000) to suggest that variations in solar irradiance are more important as a driving force in variations in climate than previously believed."

Finally, with respect to the most recent recession of Hielo Patagonico Norte outlet glaciers from their late historic moraine limits at the end of the 19th century, Glasser *et al.* say that "a similar

pattern can be observed in other parts of southern Chile (e.g., Kuylenstierna *et al.*, 1996; Koch and Kilian, 2001)," to which we would also add the findings of Kaser and Georges (1997) for the Peruvian Cordillera Blanca and Francou *et al.* (2003) for the Bolivian Cordillera Real. Likewise, they note that "in areas peripheral to the North Atlantic and in central Asia the available evidence shows that glaciers underwent significant recession at this time (cf. Grove, 1988; Savoskul, 1997)," all of which evidence points to the operation of a globally-distributed forcing factor such as that provided by *cyclically-varying solar activity*.

In light of this significant body of evidence, and Glasser *et al.*'s analysis of it, it would appear that the history of glacial activity they describe suggests the existence of a millennial-scale oscillation of climate that operates on a broad scale that may, in fact, include the entire earth. Viewed in this light, the current recession of many of earth's glaciers is seen to be but the most recent and still-ongoing phase of a naturally-recurring phenomenon that has been "doing its thing," over and over, *without any help from variable atmospheric CO<sub>2</sub> concentrations*, throughout the entire last half of the Holocene.

But the story continues.

Based on various types of evidence collected by many investigators over the years, Georges (2004) constructed a 20th-century history of glacial fluctuations in the Cordillera Blanca of Peru, which is the largest glaciated area within the tropics. This history reveals, in Georges words, that "the beginning of the century was characterized by a glacier recession of unknown extent, followed by a marked readvance in the 1920s that nearly reached the Little Ice Age maximum." Then came the "very strong" 1930s-1940s glacial mass *shrinkage*, after which there was a period of quiescence that was followed by an "intermediate retreat from the mid-1970s until the end of the century."

In comparing the two periods of glacial wasting, Georges says that "the intensity of the 1930s-1940s retreat was more pronounced than that of the one at the end of the century." In fact, his graph of the ice area lost in both time periods suggests that the rate of wastage in the 1930s-1940s was *twice as great* as that of last two decades of the 20th century, which provides absolutely no support for the climate-alarmist claim that earth warmed at a rate, and to a level, that was *unprecedented over the past millennium or more* during the latter time period.

It is also interesting to note that Georges is quite at ease talking about the Little Ice Age south of the equator in Peru, which is a very long way from the lands that border the North Atlantic Ocean, which is the only region on earth where the world's climate alarmists willingly admit the existence of this chilly era of the planet's climatic history. What is perhaps even *more* interesting, however, is the fact that the glacial extensions of the Cordillera Blanca in the late 1920s were almost equivalent to those experienced there during the depths of the Little Ice Age, which is generally recognized as being the *coldest period of the current interglacial*, which suggests it is not at all strange that there should be a sizable warming of that part of the planet subsequent to its achieving a level of cold that was unprecedented over the past *several* millennia.

Moving south again, Koch and Kilian (2005) mapped and dated, by dendrochronological means, a number of moraine systems of Glaciar Lengua and neighboring glaciers of Gran Campo Nevado in the southernmost Andes of Chile, after which they compared their results with those of researchers who studied the subject in other parts of South America. According to their findings, in the Patagonian Andes "the culmination of the Little Ice Age glacier advances occurred between AD 1600 and 1700 (e.g., Mercer, 1970; Rothlisberger, 1986; Aniya, 1996)," but that "various glaciers at Hielo Patagonico Norte and Hielo Patagonico Sur also formed prominent moraines around 1870 and 1880 (Warren and Sugden, 1993; Winchester *et al.*, 2001; Luckman and Villalba, 2001)." In addition, they note that their study "further supports this scenario," and that from their observations at Glaciar Lengua and neighboring glaciers at Gran Campo Nevado, it would appear that "the 'Little Ice Age' advance was possibly the most extensive one during the Holocene for this ice cap," which harmonizes with its being the coldest period of the past *several* millennia.

Last of all, and working with biogenic silica, magnetic susceptibility, total organic carbon (TOC), total nitrogen (TN),  $\delta^{13}\text{CTOC}$ ,  $\delta^{15}\text{NTN}$  and C/N ratios derived from the sediment records of two Venezuelan watersheds, which they obtained from cores retrieved from Lakes Mucubaji and Blanca, together with ancillary data obtained from other studies that had been conducted in the same general region, Polissar *et al.* (2006) developed continuous decadal-scale histories of glacier activity and moisture balance in that part of the tropical Andes (the Cordillera de Merida) over the past millennium and a half, from which they were able to deduce contemporary histories of regional temperature and precipitation. So what did they learn?

The international team of scientists - representing Canada, Spain, the United States and Venezuela - write that "comparison of the Little Ice Age history of glacier activity with reconstructions of solar and volcanic forcing suggests that solar variability is the primary underlying cause of the glacier fluctuations," because (1) "the peaks and troughs in the susceptibility records match fluctuations of solar irradiance reconstructed from  $^{10}\text{Be}$  and  $\delta^{14}\text{C}$  measurements," (2) "spectral analysis shows significant peaks at 227 and 125 years in both the irradiance and magnetic susceptibility records, closely matching the de Vreis and Gleissberg oscillations identified from solar irradiance reconstructions," and (3) "solar and volcanic forcing are uncorrelated between AD 1520 and 1650, and the magnetic susceptibility record follows the solar-irradiance reconstruction during this interval." In addition, they write that "four glacial advances occurred between AD 1250 and 1810, coincident with solar-activity minima," and that "temperature declines of  $-3.2 \pm 1.4^\circ\text{C}$  and precipitation increases of  $\sim 20\%$  are required to produce the observed glacial responses."

In discussing their findings, Polissar *et al.* say their results "suggest *considerable* [our italics] sensitivity of tropical climate to *small* [our italics] changes in radiative forcing from solar irradiance variability," which is something many people have had difficulty accepting in prior years. Hopefully, this paper will help them "see the light" a little clearer with respect to this subject. Not to be purveyors of *too* much good news, however, the six scientists say their

findings imply "even greater probable responses to future anthropogenic forcing," and that "profound climatic impacts can be predicted for tropical montane regions."

With respect to these latter ominous remarks, we note that whereas Polissar *et al.*'s linking of significant climate changes with *solar* radiation variability is a *factual finding* of their work, their latter statements with respect to *hypothesized* CO<sub>2</sub>-induced increases in down-welling *thermal* radiation are but *speculations* that need not follow from what they learned; for the two types of radiative forcing operate quite differently from each other, and there are many contemporaneous *biological* consequences of atmospheric CO<sub>2</sub> enrichment that may produce powerful *cooling* effects on earth's climate. Hence, there is no guarantee there will be *any* net impetus for warming as the atmosphere's CO<sub>2</sub> content continues to rise.

Another point worth noting in this regard is Polissar *et al.*'s acknowledgement that "during most of the past 10,000 years, glaciers were absent from all but the highest peaks in the Cordillera de Merida," which indicates that warmer-than-present temperatures are the *norm* for this part of the planet, and that any significant warming that might yet occur in this region (as well as most of the rest of the world) would only mark a *return* to more *typical* Holocene (or current interglacial) temperatures, which have themselves been significantly lower than those of *all four prior interglacials*. What is more, atmospheric CO<sub>2</sub> concentrations were *much lower* during all of those *much warmer* periods, providing further evidence that it is the *sun* that likely rules the world's climate, and not CO<sub>2</sub>.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/s/southamgla.php>.

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## 4.2. Sea Ice

A number of claims have been made that CO<sub>2</sub>-induced global warming is melting sea ice in both the Arctic and Antarctic, and that such melting will accelerate as time passes. In this next section, we analyze Antarctic and Arctic sea ice trends as reported in the scientific literature.

### 4.2.1. Antarctic

Utilizing Special Sensor Microwave Imager data obtained from the Defense Meteorological Satellite Program (DMSP) for the period December 1987-December 1996, Watkins and Simmonds (2000) analyzed temporal trends in different measures of the sea ice that surrounds Antarctica, noting that "it has been suggested that the Antarctic sea ice may show high sensitivity to any anthropogenic increase in temperature," as per the *canary-in-the-coal-mine* concept of high-latitude amplification and early detection of CO<sub>2</sub>-induced global warming, further noting that most climate models predict that "any rise in surface temperature would result in a decrease in sea ice coverage." So what did they find?

Contrary to what one would expect on the basis of these predictions, and especially in light of what climate alarmists call the *unprecedented* warming of the past quarter-century, the two scientists observed statistically significant *increases* in both sea ice area and sea ice extent over the period studied; and when they combined their results with results for the preceding period of 1978-1987, both parameters continued to show increases over the sum of the two periods (1978-1996). In addition, they determined that the 1990s also experienced increases in the *length* of the sea ice season.

Watkins and Simmonds' findings, i.e., that Southern Ocean sea ice has increased in area, extent and season length since at least 1978, are also supported by a number of other studies. Hanna (2001), for example, published an updated analysis of Antarctic sea ice cover based on Special Sensor Microwave Imager data for the period October 1987-September 1999, finding that the serial sea ice data depict "an ongoing slight but significant hemispheric increase of 3.7(±0.3)% in extent and 6.6(±1.5)% in area." Likewise, Parkinson (2002) utilized satellite passive-microwave data to calculate and map the length of the sea-ice season throughout the Southern Ocean for each year of the period 1979-1999, finding that although there are opposing regional trends, a "much larger area of the Southern Ocean experienced an overall lengthening of the sea-ice season ... than experienced a shortening." Updating the analysis two years later for the period November 1978 through December 2002, Parkinson (2004) reported a linear increase in 12-month running means of Southern Ocean sea ice extent of 12,380 ± 1,730 km<sub>2</sub> per year.

Zwally *et al.* (2002) also utilized passive-microwave satellite data to study Antarctic sea ice trends. Over the 20-year period 1979-1998, they report that the sea ice extent of the entire Southern Ocean increased by  $11,181 \pm 4,190$  square km per year, or by  $0.98 \pm 0.37$  percent per decade, while sea ice area increased by nearly the same amount:  $10,860 \pm 3,720$  square km per year, or by  $1.26 \pm 0.43$  percent per decade. And in contradiction of the claim that earth's climate should exhibit greater extremes when warming (which climate alarmists claim is occurring), they observed that the variability of monthly sea ice extent *declined* from 4.0% over the first ten years of the record, to 2.7% over the last ten years (which have supposedly been the warmest of the past millennium, according to the world's climate alarmists).

In yet another assessment of Antarctic sea ice behavior, Yuan and Martinson (2000) analyzed Special Sensor Microwave Imager data together with data derived from brightness temperatures measured by the Nimbus-7 Scanning Multichannel Microwave Radiometer. Among other things, they determined that the mean trend in the latitudinal location of the Antarctic sea ice edge over the prior 18 years was an *equatorward expansion* of 0.011 degree of latitude per year. But that is still not the end of the scientific testimony in this case.

Vyas *et al.* (2003) analyzed data from the multi-channel scanning microwave radiometer carried aboard India's OCEANSAT-1 satellite for the period June 1999-May 2001, which they combined with data for the period 1978-1987 that were derived from space-based passive microwave radiometers carried aboard earlier Nimbus-5, Nimbus-7 and DMSP satellites to study secular trends in sea ice extent about Antarctica over the period 1978-2001. Their work revealed that the mean rate of change of sea ice extent for the entire Antarctic region over this period was an *increase* of 0.043 M km<sup>2</sup> per year. In fact, they concluded that "the increasing trend in the sea ice extent over the Antarctic region may be *slowly accelerating* in time, particularly over the last decade," noting that the "continually increasing sea ice extent over the Antarctic Southern Polar Ocean, along with the observed decreasing trends in Antarctic ice surface temperature (Comiso, 2000) over the last two decades, is paradoxical in the global warming scenario resulting from increasing greenhouse gases in the atmosphere."

In a somewhat similar study, Cavalieri *et al.* (2003) extended prior satellite-derived Antarctic sea ice records several years by bridging the gap between Nimbus 7 and earlier Nimbus 5 satellite data sets with National Ice Center digital sea ice data, finding that sea ice extent about the continent increased at a mean rate of  $0.10 \pm 0.05 \times 10^6$  km<sup>2</sup> per decade between 1977 and 2002. Likewise, Liu *et al.* (2004) used sea ice concentration data retrieved from the scanning multichannel microwave radiometer on the Nimbus 7 satellite and the spatial sensor microwave/imager on several defense meteorological satellites to develop a quality-controlled history of Antarctic sea ice variability covering the period 1979-2002, which includes different states of the Antarctic Oscillation and several ENSO events, after which they evaluated total sea ice extent and area trends by means of linear least-squares regression. They found that "overall, the total Antarctic sea ice extent (the cumulative area of grid boxes covering at least 15% ice concentrations) has shown an increasing trend ( $\sim 4,801$  km<sup>2</sup>/yr)." In addition, they determined that "the total Antarctic sea ice area (the cumulative area of the ocean actually



covered by at least 15% ice concentrations) has increased significantly by  $\sim 13,295 \text{ km}^2/\text{yr}$ , exceeding the 95% confidence level," noting that "the upward trends in the total ice extent and area are robust for different cutoffs of 15, 20, and 30% ice concentrations (used to define the ice extent and area)."

Next, on a somewhat different note, Elderfield and Rickaby (2000) concluded that the sea ice cover of the Southern Ocean during glacial periods may have been as much as double the coverage of modern winter ice, suggesting that "by restricting communication between the ocean and atmosphere, sea ice expansion also provides a mechanism for reduced  $\text{CO}_2$  release by the Southern Ocean and lower glacial atmospheric  $\text{CO}_2$ ."

Finally, we present the results of three additional papers on Antarctic sea ice that were published in 2008. In the first paper, Laine (2008) determined 1981-2000 trends of Antarctic sea-ice *concentration* and *extent*, based on the Scanning Multichannel Microwave Radiometer and Special Sensor Microwave Imagers for the spring-summer period of November/December/January. These analyses were carried out for the continent as a whole, as well as five longitudinal sectors emanating from the south pole:  $20^\circ\text{E}$ - $90^\circ\text{E}$ ,  $90^\circ\text{E}$ - $160^\circ\text{E}$ ,  $160^\circ\text{E}$ - $130^\circ\text{W}$ ,  $130^\circ\text{W}$ - $60^\circ\text{W}$ , and  $60^\circ\text{W}$ - $20^\circ\text{E}$ . Results indicated that "the sea ice concentration shows slight increasing trends in most sectors, where the sea ice extent trends seem to be near zero." As a result of these several findings, it is not surprising that Laine also reports that "the Antarctic region as a whole and all the sectors separately show slightly positive spring-summer albedo trends."

In the next study, Comiso and Nishio (2008) set out to provide updated and improved estimates of trends in Arctic and Antarctic sea ice cover for the period extending from November 1978 to December 2006, based on data obtained from the Advanced Microwave Scanning Radiometer (AMSR-E), the Special Scanning Microwave Imager (SSM/I) and the Scanning Multichannel Microwave Radiometer (SMMR), where the data from the last two instruments were adjusted to be consistent with the AMSR-E data. Their findings indicate that sea ice extent and area in the Antarctic grew by  $+0.9 \pm 0.2$  and  $+1.7 \pm 0.3\%$  per decade, respectively.

Lastly, in a study that "extends the analyses of the sea ice time series reported by Zwally *et al.* (2002) from 20 years (1979-1998) to 28 years (1979-2006)," Cavalieri and Parkinson (2008) derived new linear trends of Antarctic sea ice *extent* and *area*, based on satellite-borne passive microwave radiometer data. Results indicate that "the total Antarctic sea ice extent trend increased slightly, from  $0.96 \pm 0.61\%$  per decade to  $1.0 \pm 0.4\%$  per decade, from the 20- to 28-year period," noting that the latter trend is significant at the 95% confidence level. Corresponding numbers for the Antarctic sea ice *area* trend were  $1.2 \pm 0.7\%$  per decade and  $1.2 \pm 0.5\%$  per decade. Both sets of results also indicate a "tightening up" of the two relationships. Thus, over the last eight years of the study period, both the extent and area of Antarctic sea ice have continued to *increase*, with the former parameter increasing at a more rapid rate than it did over the 1979-1998 period.

In considering the findings of the several research papers described above that apply to the last few decades, if one were to infer anything about the planet in terms of what state-of-the-art climate models predict and what is known about real-world sea ice behavior around Antarctica, one would be tempted to conclude that the globe is currently in a *cooling* mode. Does that mean that the IPCC-endorsed air temperature history of the planet is in error? Or does it mean that the climate models are in error? Or does it mean that both are in error? All three of these important questions need to be pondered before rushing headlong into adopting expensive and economy-wrenching measures to battle what could well turn out to be an imaginary enemy, i.e., CO<sub>2</sub>-induced global warming.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/s/seaiceantarctic.php>.

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## 4.2.2. Arctic

### 4.2.2.1. Extent

Arctic climate is incredibly complex, varying simultaneously on a number of different timescales for a number of different reasons (Venegas and Mysak, 2000); and against this backdrop of multiple causation and timeframe variability, it is extremely difficult to identify the increase in temperature that has been predicted to result from the burning of fossil fuels. The task is further complicated because many of the records that do exist contain only a few years to a few decades of data; and they yield different trends depending on the period of time studied. Such is also the case with the records of Arctic sea ice extent.

Consider, for example, the study of Johannessen *et al.* (1999), who analyzed Arctic sea ice extent over the period 1978-1998 and found it to have decreased by about 14%. This finding led them to suggest that "the balance of evidence," as small as it then was, indicates "an ice cover in transition," and that "if this apparent transformation continues, it may lead to a markedly different ice regime in the Arctic," as was also suggested by Vinnikov *et al.* (1999).

Reading Johannessen *et al.*'s assessment of the situation, one is left with the impression that a relatively consistent and ongoing transformation (a persistent reduction in the area of Arctic sea ice) is, in fact, in progress. However, and according to their own data, this assessment is highly debatable and possibly false. In viewing their plots of sea ice area, for example, it is readily evident that the decline in this parameter did not occur smoothly over the 20-year period of study. In fact, essentially all of the drop it experienced occurred rather abruptly over a single period of not more than three years (87/88-90/91) and possibly only one year (89/90-90/91). Furthermore, it could be argued from their data that from 1990/91 onward, sea ice area in the Arctic may have actually *increased*.

Support for this argument is found in the study of Kwok (2004), who estimated "the time-varying perennial ice zone (PIZ) coverage and construct[s] the annual cycles of multiyear (MY, including second year) ice coverage of the Arctic Ocean using QuikSCAT backscatter, MY fractions from RADARSAT, and the record of ice export from satellite passive microwave observations" for the years 199-2003. Based on the above-described data, Kwok calculated that the coverage of Arctic MY sea ice at the beginning of each year of the study was  $3774 \times 10^3 \text{ km}^2$  in 2000,  $3896 \times 10^3 \text{ km}^2$  in 2001,  $4475 \times 10^3 \text{ km}^2$  in 2002, and  $4122 \times 10^3 \text{ km}^2$  in 2003, representing an *increase* in sea ice coverage of 9% over but a *third* of a decade.

More questions are raised by the study of Parkinson (2000b), who utilized satellite-derived data of sea ice extent to calculate changes in this parameter for the periods 1979-1990 and 1990-1999. They report that in seven of the nine regions into which they divided the Arctic for their analysis, the "sign of the trend reversed from the 1979-1990 period to the 1990-1999 period," indicative of the ease with which significant decadal trends are often reversed in this part of the world.

In another study, Belchansky *et al.* (2004) report that from 1988 to 2001, total January multiyear ice area declined at a mean rate of 1.4% per year. In the autumn of 1996, however, they note that "a large multiyear ice recruitment of over  $10^6$  km<sup>2</sup> *fully replenished* [our italics] the previous 8-year decline in total area," but they add that the monumental replenishment "was followed by an accelerated and compensatory decline during the subsequent 4 years." In addition, they learned that 75% of the interannual variation in January multiyear sea area "was explained by linear regression on two atmospheric parameters: the previous winter's Arctic Oscillation index as a proxy to melt duration and the previous year's average sea level pressure gradient across the Fram Strait as a proxy to annual ice export."

Belchansky *et al.* conclude that their 14-year analysis of multiyear ice dynamics is "insufficient to project long-term trends." Hence, they also conclude it is insufficient to reveal "whether recent declines in multiyear ice area and thickness are indicators of anthropogenic exacerbations to positive feedbacks that will lead the Arctic to an unprecedented future of reduced ice cover [the climate-alarmist position], or whether they are simply ephemeral expressions of natural low frequency oscillations [our position]." It should be noted in this regard, however, that *low frequency oscillations are what the data actually reveal*; and such behavior is *not* what one would predict from a gradually increasing atmospheric CO<sub>2</sub> concentration.

In another study, Heige-Jorgensen and Laidre (2004) examined changes in the fraction of open-water found within various pack-ice microhabitats of Foxe Basin, Hudson Bay, Hudson Strait, Baffin Bay-Davis Strait, northern Baffin Bay and Lancaster Sound over a 23-year interval (1979-2001) using remotely-sensed microwave measurements of sea-ice extent, after which the trends they documented were "related to the relative importance of each wintering microhabitat for eight marine indicator species and potential impacts on winter success and survival were examined."

Results of the analysis indicate that Foxe Basin, Hudson Bay and Hudson Strait showed small increasing trends in the fraction of open-water, with the upward trends at all microhabitats studied ranging from 0.2 to 0.7% per decade. In Baffin Bay-Davis Strait and northern Baffin Bay, on the other hand, the open-water trend was *downward*, and at a mean rate for all open-water microhabitats studied of fully 1% per decade, while the trend in all Lancaster Sound open-water microhabitats was also downward, in this case at a mean rate of 0.6% per decade. With respect to the context of these open-water declines, Heide-Jorgensen and Laidre report that "increasing trends in sea ice coverage in Baffin Bay and Davis Strait (resulting in declining

open-water) were as high as 7.5% per decade between 1979-1999 (Parkinson *et al.*, 1999; Deser *et al.*, 2000; Parkinson, 2000a,b; Parkinson and Cavalieri, 2002) and comparable significant increases have been detected back to 1953 (Stern and Heide-Jorgensen, 2003)." They additionally note that "similar trends in sea ice have also been detected locally along the West Greenland coast, with slightly lower increases of 2.8% per decade (Stern and Heide-Jorgensen, 2003)."

Another example of changing sea ice trends is provided by the study of Cavalieri *et al.* (2003), who extended prior satellite-derived Arctic sea ice records several years back in time by bridging the gap between Nimbus 7 and earlier Nimbus 5 satellite data sets via comparisons with National Ice Center digital sea ice data. For the newly-extended period of 1972-2002, they determined that Arctic sea ice extent had declined at a mean rate of  $0.30 \pm 0.03 \times 10^6$  km<sup>2</sup> per decade; while for the shortened period from 1979-2002, they found a mean rate of decline of  $0.36 \pm 0.05 \times 10^6$  km<sup>2</sup> per decade, or at a rate that was 20% greater than the full-period rate. In addition Serreze *et al.* (2002) determined that the downward trend in Arctic sea ice extent during the passive microwave era culminated with a record minimum value in 2002.

These results could readily be construed to be compatible with the spin that is typically given them by climate alarmists; that is, they indicate an increasingly greater rate of Arctic sea ice melting during the latter part of the 20th century, when global warming is claimed to have occurred at an increasingly greater rate. However, the results of these studies are not the end of the story, for still other studies have analyzed Arctic sea ice extent beyond the observational record using proxy data sources; and their results must be considered as well. As Grumet *et al.* (2001) have described the situation, recent trends in Arctic sea ice cover "can be viewed out of context because their brevity does not account for interdecadal variability, nor are the records sufficiently long to clearly establish a climate trend."

In an effort to overcome this "short-sightedness," Grumet *et al.* developed a 1000-year record of spring sea ice conditions in the Arctic region of Baffin Bay based on sea-salt records from an ice core obtained from the Penny Ice Cap on Baffin Island. In doing so, they determined that after a period of reduced sea ice during the 11th-14th centuries, enhanced sea ice conditions prevailed during the following 600 years. For the final century of this period, however, they report that "despite warmer temperatures during the turn of the century, sea-ice conditions in the Baffin Bay/Labrador Sea region, at least during the last 50 years, are within 'Little Ice Age' variability," suggesting that sea ice extent there has not yet emerged from the range of conditions characteristic of the Little Ice Age.

In an adjacent sector of the Arctic, this latter period of time was also studied by Comiso *et al.* (2001), who used satellite imagery to analyze and quantify a number of attributes of the Odden ice tongue - a winter ice-cover phenomenon that occurs in the Greenland Sea with a length of about 1300 km and an aerial coverage of as much as 330,000 square kilometers - over the period 1979-1998. By additionally utilizing surface air temperature data from Jan Mayen Island, which is located within the region of study, they were able to infer the behavior of this phenomenon over the past 75 years. Trend analyses revealed that the ice tongue has exhibited

no statistically significant change in any of the parameters studied over the past 20 years; but the proxy reconstruction of the Odden ice tongue for the past 75 years revealed the ice phenomenon to have been "a relatively smaller feature several decades ago," due to the warmer temperatures that prevailed at that time.

In another study of Arctic climate variability, Omstedt and Chen (2001) obtained a proxy record of the annual maximum extent of sea ice in the region of the Baltic Sea over the period 1720-1997. In analyzing this record, they found that a significant decline in sea ice occurred around 1877. In addition, they reported finding greater variability in sea ice extent in the colder 1720-1877 period than in the warmer 1878-1997 period.

Also at work in the Baltic Sea region, Jevrejeva (2001) reconstructed an even longer record of sea ice duration (and, therefore, extent) by examining historical data for the observed time of ice break-up between 1529 and 1990 in the northern port of Riga, Latvia. The long date-of-ice-break-up time series was best described by a fifth-order polynomial, which identified four distinct periods of climatic transition: (1) 1530-1640, warming with a tendency toward earlier ice break-up of 9 days/century, (2) 1640-1770, cooling with a tendency toward later ice break-up of 5 days/century, (3) 1770-1920, warming with a tendency toward earlier ice break-up of 15 days/century, and (4) 1920-1990, *cooling with a tendency toward later ice break-up of 12 days/century*.

On the other hand, in a study of the Nordic Seas (the Greenland, Iceland, Norwegian, Barents and Western Kara Seas), Vinje (2001) determined that "the extent of ice in the Nordic Seas measured in April has decreased by 33% over the past 135 years." He notes, however, that "nearly half of this reduction is observed over the period 1860-1900," and we note, in this regard, that the first half of this sea-ice decline occurred over a period of time when the atmosphere's CO<sub>2</sub> concentration rose by only 7 ppm, whereas the second half of the sea-ice decline occurred over a period of time when the air's CO<sub>2</sub> concentration rose by more than 70 ppm. This observation clearly suggests that if the historical rise in the air's CO<sub>2</sub> content has been responsible for the historical decrease in sea-ice extent, its impact over the last century has *declined to less than a tenth* of what its impact was over the preceding four decades, which in turn suggests that the increase in the air's CO<sub>2</sub> content over the past 135 years has likely had nothing whatsoever to do with the concomitant decline in sea-ice cover.

In a similar study of the Kara, Laptev, East Siberian and Chuckchi Seas, based on newly available long-term Russian observations, Polyakov *et al.* (2002) found "smaller than expected" trends in sea ice cover that, in their words, "do not support the hypothesized polar amplification of global warming." Likewise, in a second study published the following year, Polyakov *et al.* (2003) report that "over the entire Siberian marginal-ice zone the century-long trend is only -0.5% per decade," while "in the Kara, Laptev, East Siberian, and Chukchi Seas the ice extent trends are not large either: -1.1%, -0.4%, +0.3% and -1.0% per decade, respectively." Moreover, they say that "these trends, except for the Chukchi Sea, are not statistically significant," which observations tend to discredit climate model *qualitative* predictions of

*amplified warming in earth's polar regions* in response to increases in the air's CO<sub>2</sub> content, which in turn tends to discredit their *quantitative* predictions of CO<sub>2</sub>-induced global warming.

In another study, Divine and Dick (2006) used historical April through August ice observations made in the Nordic Seas - comprised of the Iceland, Greenland, Norwegian and Barents Seas, extending from 30°W to 70°E - to construct time series of ice-edge position anomalies spanning the period 1750-2002, which they analyzed for evidence of long-term trend and oscillatory behavior. The authors report that "evidence was found of oscillations in ice cover with periods of about 60 to 80 years and 20 to 30 years, superimposed on a continuous negative trend," which observations are indicative of a "persistent ice retreat since the second half of the 19th century" that began well before anthropogenic CO<sub>2</sub> emissions could have had much of an effect on earth's climate.

Noting that the last cold period observed in the Arctic occurred at the end of the 1960s, the two Norwegian researchers say their results suggest that "the Arctic ice pack is now at the periodical apogee of the low-frequency variability," and that "this could explain the strong negative trend in ice extent during the last decades as a possible superposition of natural low frequency variability and greenhouse gas induced warming of the last decades." *However*, as they immediately caution, "a similar shrinkage of ice cover was observed in the 1920s-1930s, during the previous warm phase of the low frequency oscillation, when any anthropogenic influence is believed to have still been negligible." They suggest, therefore, "that during decades to come ... the retreat of ice cover may change to an expansion."

In light of this litany of findings, it is difficult to accept the alarmist position that Northern Hemispheric sea ice is rapidly disintegrating in response to CO<sub>2</sub>-induced global warming. Rather, the oscillatory behavior observed in so many of the sea ice studies suggests, in the words of Parkinson (2000), "the possibility of close connections between the sea ice cover and major oscillatory patterns in the atmosphere and oceans," including connections with: "(1) the North Atlantic Oscillation (e.g., Hurrell and van Loon, 1997; Johannessen *et al.*, 1999; Kwok and Rothrock, 1999; Deser *et al.*, 2000; Kwok, 2000, Vinje, 2001) and the spatially broader Arctic Oscillation (e.g., Deser *et al.*, 2000; Wang and Ikeda, 2000); (2) the Arctic Ocean Oscillation (Polyakov *et al.*, 1999; Proshutinsky *et al.*, 1999); (3) a 'see-saw' in winter temperatures between Greenland and northern Europe (Rogers and van Loon, 1979); and (4) an interdecadal Arctic climate cycle (Mysak *et al.*, 1990; Mysak and Power, 1992)." The likelihood that Arctic sea ice trends are the product of such natural oscillations, Parkinson continues, "provides a strong rationale for considerable caution when extrapolating into the future the widely reported decreases in the Arctic ice cover over the past few decades or when attributing the decreases primarily to global warming," a caution with which we heartily agree.

One final study of note that should be mentioned here is that of Bamber *et al.* (2004), who used high-accuracy ice-surface elevation measurements (Krabill *et al.*, 2000) of the largest ice cap in the Eurasian Arctic -- Austfonna, on the island of Nordaustlandet in northeastern Svalbard -- to evaluate ice cap elevation changes between 1996 and 2002. They determined that the central and highest-altitude area of the ice cap, which comprises 15% of its total area, "increased in

elevation by an average of 50 cm per year between 1996 and 2002," while "to the northeast of this region, thickening of about 10 cm per year was also observed." They further note that the highest of these growth rates represents "as much as a 40% increase in accumulation rate (Pinglot *et al.*, 2001)."

Based on the ancillary sea-ice and meteorological data they analyzed, Bamber *et al.* concluded that the best explanation for the dramatic increase in ice cap growth over the six-year study period was a large increase in precipitation caused by a concomitant reduction in sea-ice cover in this sector of the Arctic. Their way of characterizing this phenomenon is simply to say that it represents the transference of ice from the top of the sea (in this case, the Barents Sea) to the top of the adjacent land (in this case, the Austfonna ice cap). And as what has been observed to date is but the *beginning* of the phenomenon, which will become even stronger in the absence of nearby sea-ice, "projected changes in Arctic sea-ice cover," as they say in the concluding sentence of their paper, "will have a significant impact on the mass-balance of land ice around the Arctic Basin over at least the next 50 years," which result, we might add, may well be far, far different from what the world's climate alarmists are currently anticipating.

Yes, the tales told by Arctic sea ice behavior are many and varied, as well as incomplete and even contradictory in some instances. It will thus be a very long time indeed before we can accurately decipher the grand message they contain, if there even is a grand message, which is by no means certain.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/s/seaicearctic.php>.

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#### 4.2.2.2. Thickness

Based on analyses of submarine sonar data, Rothrock *et al.* (1999) and Wadhams and Davis (2000) suggested that Arctic sea ice had thinned by nearly 50% over the prior few decades. Their reports were widely cited by both the Intergovernmental Panel on Climate Change (IPCC: Houghton *et al.*, 2001) and by the popular media, who at the time of the publications' appearance were whipped into a frenzy by climate-alarmist claims that the sea-ice thinning was caused by global warming that had been induced by anthropogenic CO<sub>2</sub> emissions.

So how has this contention withstood the test of time, albeit of but a few short years' duration? The first hint of an answer appeared essentially simultaneously with the publication of the ominous reports, when Johannessen *et al.* (1999) used surface-based measurements to derive variations in area-averaged Arctic sea-ice thickness from 1978 to 1991. They, too, detected a downward trend in this parameter. However, in carefully scrutinizing their data, it can be seen that the decline in sea-ice thickness did not occur smoothly over the period of study. In fact, essentially all of the drop occurred rather abruptly over a single period of not more than three years (1987/88-1990/91) and possibly only one year (1989/90-1990/91).

The next chapter in the complex detective story occurred two years later, when Winsor (2001) analyzed a much more comprehensive set of Arctic sea-ice data that had been obtained from six submarine cruises conducted between 1991 and 1997 that had covered the central Arctic Basin from 76° N to 90° N, as well as two areas that had been particularly densely sampled, one centered around the North Pole (>87° N) and one in the central part of the Beaufort Sea (centered at approximately 76° N, 145°W). The transect data across the entire Arctic Basin revealed that the mean Arctic sea-ice thickness had remained "almost constant" over the period of study. Data from the North Pole also showed little variability, and a linear regression of the data revealed a "slight increasing trend for the whole period." As for the Beaufort Sea region, annual variability in sea ice thickness was greater than at the North Pole; but once again, in Winsor's words, "no significant trend" in mean sea-ice thickness was found. Combining the North Pole results with the results of an earlier study, Winsor thus concluded

that "mean ice thickness has remained on a near-constant level around the North Pole from 1986 to 1997."

The following year, Holloway and Sou (2002) explored "how observations, theory, and modeling work together to clarify perceived changes to Arctic sea ice," incorporating data from "the atmosphere, rivers, and ocean along with dynamics expressed in an ocean-ice-snow model." On the basis of a number of different data-fed model runs, they found that for the last half of the past century, "no linear trend [in Arctic sea ice volume] over 50 years is appropriate," noting that their results indicated "increasing volume to the mid-1960s, decadal variability without significant trend from the mid-1960s to the mid-1980s, then a loss of volume from the mid-1980s to the mid-1990s." The net effect of this behavior, in their words, was that "the volume estimated in 2000 is close to the volume estimated in 1950." Hence, they suggested that the initial inferred rapid thinning of Arctic sea ice was, as they put it, "unlikely," due to problems arising from under sampling. They also reported that "varying winds that readily redistribute Arctic ice create a recurring pattern whereby ice shifts between the central Arctic and peripheral regions, especially in the Canadian sector," and that the "timing and tracks of the submarine surveys missed this dominant mode of variability."

In the same year, Polyakov *et al.* (2002) employed newly available long-term Russian fast-ice data obtained from the Kara, Laptev, East Siberian and Chuckchi Seas to investigate trends and variability in the Arctic environment poleward of 62°N. This study revealed that fast-ice thickness trends in the different seas were "relatively small, positive or negative in sign at different locations, and not statistically significant at the 95% level." A year later, these results were reconfirmed by Polyakov *et al.* (2003), who reported that the available fast-ice records "do not show a significant trend," while noting that "in the Kara and Chukchi Seas trends are positive, and in the Laptev and East Siberian Seas trends are negative," but stating that "these trends are not statistically significant at the 95% confidence level."

The following year, Laxon *et al.* (2003) used an eight-year time series (1993-2001) of Arctic sea-ice thickness data derived from measurements of ice freeboard made by radar altimeters carried aboard ERS-1 and 2 satellites to determine the mean thickness and variability of Arctic sea ice between latitudes 65 and 81.5°N, which region covers the entire circumference of the Arctic Ocean, including the Beaufort, Chukchi, East Siberian, Kara, Laptev, Barents and Greenland Seas. These real-world observations served a number of purposes: (1) they revealed "an interannual variability in ice thickness at higher frequency, and of greater amplitude, than simulated by regional Arctic models," (2) they undermined "the conclusion from numerical models that changes in ice thickness occur on much longer timescales than changes in ice extent," and (3) they showed that "sea ice mass can change by up to 16% within one year," which finding "contrasts with the concept of a slowly dwindling ice pack, produced by greenhouse warming." Laxon *et al.* thus concluded that "errors are present in current simulations of Arctic sea ice," stating in their closing sentence that "until models properly reproduce the observed high-frequency, and thermodynamically driven, variability in sea ice thickness, simulations of both recent, and future, changes in Arctic ice cover will be open to question."

Next, based on monthly fields of ice motion obtained from the International Arctic Buoy Program, Pfirman *et al.* (2004) analyzed Arctic sea-ice drift dynamics from 1979-1997, using a Lagrangian perspective that "shows the complexities of ice drift response to variations in atmospheric conditions." This analysis indicated, in their words, that "large amounts of sea ice form over shallow Arctic shelves, are transported across the central basin and are exported primarily through Fram Strait and, to lesser degrees, the Barents Sea and Canadian Archipelago," consistent with the observations of several other investigators. They also determined that within the central Arctic, ice travel times averaged 4.0 years from 1984-85 through 1988-89, but only 3.0 years from 1990-91 through 1996-97. This enhanced rate of export of old ice to Fram Strait from the Beaufort Gyre over the latter period decreased the fraction of thick ridged ice within the central basin of the Arctic, and was deemed by Pfirman *et al.* to be responsible for some of the sea-ice thinning observed between the 1980s and 1990s. They also note that the rapid change in ice dynamics that occurred between 1988 and 1990 was "in response to a weakening of the Beaufort high pressure system and a strengthening of the European Arctic low (a shift from lower North Atlantic Oscillation/Arctic Oscillation to higher NAO/OA index) [Walsh *et al.*, 1996; Proshutinsky and Johnson, 1997; Kwok, 2000; Zhang *et al.*, 2000; Rigor *et al.*, 2002]."

Lastly, in a paper on landfast ice in Canada's Hudson Bay, Gagnon and Gough (2006) cite nine different studies of sea-ice cover, duration and thickness in the Northern Hemisphere, noting that the Hudson Bay region "has been omitted from those studies with the exception of Parkinson *et al.* (1999)," which makes one wonder *why*. For 13 stations located on the shores of Hudson Bay (7) and surrounding nearby lakes (6), Gagnon and Gough then analyzed long-term weekly measurements of ice thickness and associated weather conditions that began and ended, in the mean, in 1963 and 1993, respectively.

Results of the study revealed that a "statistically significant thickening of the ice cover over time was detected on the western side of Hudson Bay, while a slight thinning *lacking statistical significance* [our italics] was observed on the eastern side." This asymmetry, in their words, was "related to the variability of air temperature, snow depth, and the dates of ice freeze-up and break-up," with "increasing maximum ice thickness at a number of stations" being "correlated to earlier freeze-up due to negative temperature trends in autumn," and with high snow accumulation being associated with low ice thickness, "because the snow cover insulates the ice surface, reducing heat conduction and thereby ice growth." Noting that their findings "are in contrast to the projections from general circulation models, and to the reduction in sea-ice extent and thickness observed in other regions of the Arctic," Gagnon and Gough say "this contradiction must be addressed in regional climate change impact assessments," rather, we would add, than simply being *ignored*.

These observations suggest that much of the reported thinning of Arctic sea ice that occurred in the 1990s -- *if real*, as per Winsor (2001) -- was *not* the result of CO<sub>2</sub>-induced global warming, as claimed at the time by many alarmists. Rather, it was a natural consequence of changes in ice dynamics caused by an atmospheric *regime shift*, of which there have been several in decades

past and will likely be several in decades to come, totally irrespective of past or future changes in the air's CO<sub>2</sub> content. Whether *any* portion of possible past sea ice thinning was due to global warming is consequently still impossible to know, for temporal variability in Arctic sea-ice behavior is simply too great to allow such a small and slowly-developing signal to be detected yet. In describing an earlier regime shift, for example, Dumas *et al.* (2003) noted that "a sharp decrease in ice thickness of roughly 0.6 m over 4 years (1970-74) [was] followed by an abrupt increase of roughly 0.8 m over 2 years (1974-76)."

In view of these several observations, it will likely be a number of years before anything definitive can be said about CO<sub>2</sub>-induced global warming on the basis of the thickness of Arctic sea-ice, other than that its impact on sea-ice thickness is much too small to be detected at the present time.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/s/seaicearcticthick.php>.

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### **4.3. Precipitation Trends**

In spite of the fact that GCMs have failed to accurately reproduce observed patterns and totals of precipitation (Lebel *et al.*, 2000), model predictions of imminent CO<sub>2</sub>-induced global warming often suggest that this phenomenon should lead to increases in rainfall amounts and intensities. Hence, many scientists are examining historical precipitation records in an effort to determine how temperature changes of the past millennium have impacted these aspects of earth's hydrologic cycle. In this section, we review what some of them have learned about rainfall across the globe, starting with Africa.

Additional information on this subject, including reviews on precipitation topics not discussed here, can be found at [http://www.co2science.org/subject/p/subject\\_p.php](http://www.co2science.org/subject/p/subject_p.php).

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#### 4.3.1. Africa

Beginning in southern Africa, Richard *et al.* (2001) analyzed summer (Jan-Mar) rainfall totals over the period 1900-1998, finding that interannual variability was higher for the periods 1900-1933 and 1970-1998, but lower for the period 1934-1969. The strongest rainfall anomalies (greater than two standard deviations) were observed at the beginning of the century. However, the authors conclude there were "no significant changes in the January-March rainfall totals," nor any evidence of "abrupt shifts during the 20th century," suggesting that rainfall trends in southern Africa do not appear to have been influenced by CO<sub>2</sub>-induced - or any other type of - global warming.

Moving to the equatorial region of East Africa, Nicholson and Yin (2001) report there have been "two starkly contrasting climatic episodes" since the late 1700s. The first, which began sometime prior to 1800, was characterized by "drought and desiccation." Extremely low lake levels were the norm, as drought reached its extreme during the 1820s and 1830s. In the mid to latter part of the 1800s, however, the drought began to weaken and floods became "continually high," but by the turn of the century lake levels began to fall as mild drought conditions returned. The drought did not last long, however, and the latter half of the 20th Century has seen an enhanced hydrologic cycle with a return of some lake levels to the high stands of the mid to late 1800s.

Verschuren *et al.* (2000) also examined hydrologic conditions in equatorial East Africa, but over a much longer time scale, i.e., a full thousand years. They report the region was significantly drier than it is today during the Medieval Warm Period from AD 1000 to 1270, while it was relatively wet during the Little Ice Age from AD 1270 to 1850. However, this latter period was interrupted by three episodes of prolonged dryness: 1390-1420, 1560-1625 and 1760-1840. These "episodes of persistent aridity," according to the authors, were "more severe than any recorded drought of the twentieth century."

The dry episode of the late 18th / early 19th centuries recorded in Eastern Africa has also been identified in Western Africa. In analyzing the climate of the past two centuries, Nicholson (2001) reports that the most significant climatic change that has occurred "has been a long-term reduction in rainfall in the semi-arid regions of West Africa," which has been "on the order of 20 to 40% in parts of the Sahel." There have been, she says, "three decades of protracted aridity," and "nearly all of Africa has been affected ... particularly since the 1980s." However, she goes on to note that "the rainfall conditions over Africa during the last 2 to 3 decades are not unprecedented," and that "a similar dry episode prevailed during most of the first half of the 19th century."

The importance of these findings is best summarized by Nicholson herself, when she states that "the 3 decades of dry conditions evidenced in the Sahel are not in themselves evidence of



irreversible global change." And especially, we would add, are they not evidence of global warming-induced change. Why not (to both points)? Because a longer historical perspective of the type we are constantly striving to obtain clearly indicates, in the first instance, that an even longer period of similar dry conditions occurred between 1800 and 1850. And in the second instance, this remarkable dry period occurred when the earth was still in the clutches of the Little Ice Age, a period of cold that is without precedent in at least the last 6500 years ... *even in Africa* (Lee-Thorp *et al.*, 2001). Hence, there is no reason to think that the past two- to three-decade Sahelian drought is in any way unusual or that it was caused by the putative higher temperatures of that period. Simply put, like many other things, *droughts happen*.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/p/precipafrika.php>.

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### 4.3.2. Arctic

Rawlins *et al.* (2006) state that "warming is predicted to enhance atmospheric moisture storage resulting in increased net precipitation," citing as the basis for this statement the Arctic Climate Impact Assessment (2005). Likewise, Peterson *et al.* (2002) have written that "both theoretical arguments and models suggest that net high-latitude precipitation increases in proportion to increases in mean hemispheric temperature," citing the works of Manaabe and Stouffer (1994) and Rahmstorf and Ganopolski (1999). Do real-world data bear them out? In the paragraphs that follow, we evaluate this question in light of the results of three studies that come to bear upon it.

Curtis *et al.* (1998) examined a number of climatic variables at two first-order Arctic weather stations (Barrow and Barter Island, Alaska) that began in 1949, finding that both the frequency

and mean intensity of precipitation at these two locations decreased over the period of record. Contemporaneously, they report that temperatures in the western Arctic increased, but that "the observed mean increase varies strongly from month-to-month making it difficult to explain the annual trend solely on the basis of an anthropogenic effect resulting from the increase in greenhouse gases in the atmosphere." Be that as it may, the four researchers concluded that the theoretical model-based assumption that "increased temperature leads to high precipitation ... is not valid," at least for the part of the western Arctic that was the focus of their analysis.

Lamoureux (2000) analyzed varved lake sediments obtained from Nicolay Lake, Cornwall Island, Nunavut, Canada, which were compared with rainfall events recorded at a nearby weather station over the period 1948-1978 and thereby used to reconstruct a rainfall history for the surrounding region over the 487-year period from 1500 to 1987. The results were suggestive of a small, but statistically insignificant, increase in rainfall over the course of the record. However, *heavy* rainfall was most frequent during the 17th and 19th centuries, which were the *coldest* periods of the past 400 years in the Canadian High Arctic, as well as the Arctic as a whole. In addition, Lamoureux found that "more frequent extremes and increased variance in yield occurred during the 17th and 19th centuries, likely due to increased occurrences of cool, *wet* [our italics] synoptic types during the *coldest* [our italics] periods of the *Little Ice Age* [our italics]." Consequently, the results of this study also contradict the story promulgated by climate alarmists relative to the effects of global warming on extreme weather events and weather variability, both of which are typically claimed to increase with an increase in air temperature. Here, however, in a part of the planet predicted to be most impacted by CO<sub>2</sub>-induced global warming -- the Canadian High Arctic -- a warming of the climate is demonstrated to *reduce* weather extremes related to precipitation.

Most recently, Rawlins *et al.* (2006) calculated trends in the spatially-averaged water equivalent of annual rainfall and snowfall across the six largest Eurasian drainage basins that feed major rivers that deliver water to the Arctic Ocean for the period 1936-1999, over which time interval climate alarmists claim the globe's mean temperature rose to a level -- and at a rate -- that was *unprecedented over the past two millennia*. Their results indicated that annual rainfall across the total area of the six basins decreased consistently and significantly over the 64-year period. Annual snowfall, on the other hand, exhibited "a strongly significant increase," but only "until the late 1950s." Thereafter, it exhibited "a moderately significant decrease," so that "no significant change [was] determined in Eurasian-basin snowfall over the entire 64 year period." The researchers' bottom-line finding, therefore, was that annual *total* precipitation (including both rainfall and snowfall) *decreased* over the period of their study; and they note that this finding is "consistent with the reported (Berezovskaya *et al.*, 2004) decline in total precipitation."

In light of the findings reviewed above, either (1) the theoretical arguments and model predictions that suggest that "high-latitude precipitation increases in proportion to increases in mean hemispheric temperature" are not incredibly robust, or (2) late 20th-century temperatures may not have been much warmer than those of the mid-1930s and 40s, or (3)

both of the above, any or all of which choices fail to provide support for the standard alarmist scenario of catastrophic CO<sub>2</sub>-induced global warming and its many conjectured negative planetary impacts.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/p/preciparctic.php>.

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### 4.3.3. Asia

Kripalani *et al.* (2003) note that globally-averaged temperatures are projected to rise under all scenarios of future energy use, according to the IPCC, leading to "increased variability and strength of the Asian monsoon." Consequently, to see if there is any sign of such a precipitation response in real-world measurements, they examined Indian monsoon rainfall using observational data for the period 1871-2001 that were obtained from 306 stations

distributed across the country. In doing so, they discovered decadal variations running throughout the record that reveal "distinct alternate epochs of above and below normal rainfall," which epochs "tend to last for about three decades." In addition, they report "there is no clear evidence to suggest that the strength and variability of the Indian Monsoon Rainfall (IMR) nor the epochal changes are affected by the global warming." They also report that "studies by several authors in India have shown that there is no statistically significant trend in IMR for the country as a whole." Last of all, they report that "Singh (2001) investigated the long term trends in the frequency of cyclonic disturbances over the Bay of Bengal and the Arabian Sea using 100-year (1890-1999) data and found significant *decreasing* trends [our italics]." As a result, Kripalani *et al.* conclude that "there seem[s] to be no support for the intensification of the monsoon nor any support for the increased hydrological cycle as hypothesized by [the] greenhouse warming scenario in model simulations." In addition, they say that "the analysis of observed data for the 131-year period (1871-2001) suggests no clear role of global warming in the variability of monsoon rainfall over India," much as Kripalani and Kulkarni (2001) had concluded two years earlier. Hence, it is *doubly* clear that the climate models appear to have struck out with respect to both of their Asian monsoon-related projections.

Kanae *et al.* (2004) also note that both the number and intensity of heavy precipitation events are projected to increase in a warming world, according to the IPCC. Hence, they investigate this climate-model-derived hypothesis with digitalized hourly precipitation data recorded at the Tokyo Observatory of the Japan Meteorological Agency for the period 1890-1999. Within this context, they report that "many hourly heavy precipitation events (above 20 mm/hour) occurred in the 1990s compared with the 1970s and the 1980s," and that against that backdrop, "the 1990s seems to be unprecedented." However, they note that "hourly heavy precipitation around the 1940s is even stronger/more frequent than in the 1990s." In fact, their plots of maximum hourly precipitation and the number of extreme hourly precipitation events rise fairly regularly from the 1890s to peak in the 1940s, after which declines set in that bottom out in the 1970s and then reverse to rise to endpoints in the 1990s that *are not yet as high as the peaks of the 1940s*.

Taking a somewhat longer view of the subject, Pederson *et al.* (2001) used tree-ring chronologies from northeastern Mongolia to reconstruct annual precipitation and streamflow histories for the period 1651-1995. Analyses of both standard deviations and five-year intervals of extreme wet and dry periods of this record revealed that "variations over the recent period of instrumental data are not unusual relative to the prior record." The authors do state, however, that the reconstructions "appear to show more frequent extended wet periods in more recent decades," but they say this observation "does not demonstrate unequivocal evidence of an increase in precipitation as suggested by some climate models." In addition, they report that spectral analysis of the data revealed significant periodicities around 12 and 20-24 years, suggesting, in their words, "possible evidence for solar influences in these reconstructions for northeastern Mongolia."

Going back even further in time, Touchan *et al.* (2003) developed two reconstructions of spring (May-June) precipitation for southwestern Turkey from tree-ring width measurements, one of

which extended from 1776 to 1998 and one from 1339 to 1998. These reconstructions, in their words, "show clear evidence of multi-year to decadal variations in spring precipitation," but they report that "dry periods of 1-2 years were well distributed throughout the record" and that the same was true of wet periods of 1-2 years' duration. With respect to more extreme events, however, the period that preceded the Industrial Revolution stood out. They say, for example, that "all of the wettest 5-year periods occurred prior to 1756," while the longest period of reconstructed spring drought was the four-year period 1476-79, and the single driest spring was 1746. Hence, it is clear that Turkey's greatest precipitation extremes occurred *prior* to the Modern Warm Period, which is just the *opposite* of what climate alarmists typically claim about extreme weather and its response to global warming.

Looking *much* further back in time (from 9600 to 6100 years ago) were Neff *et al.* (2001), who explored the relationship between a  $^{14}\text{C}$  tree-ring record and a  $\delta^{18}\text{O}$  proxy record of monsoon rainfall intensity as recorded in calcite  $\delta^{18}\text{O}$  data obtained from a stalagmite in northern Oman. They found that the correlation between the two data sets was "extremely strong," and that a spectral analysis of the data revealed statistically significant periodicities centered on 779, 205, 134 and 87 years for the  $\delta^{18}\text{O}$  record and periodicities of 206, 148, 126, 89, 26 and 10.4 years for the  $^{14}\text{C}$  record. Consequently, because variations in  $^{14}\text{C}$  tree-ring records are generally attributed to variations in solar activity, and because of the  $^{14}\text{C}$  record's strong correlation with the  $\delta^{18}\text{O}$  record, as well as the closely corresponding results of their spectral analyses, Neff *et al.* conclude there is "solid evidence" that both signals are responding to solar forcing.

In conclusion, the evidence reviewed here provides absolutely no support for the point of view that precipitation in a warming world becomes more variable and intense. In fact, in some cases it tends to suggest just the opposite, and provides support for the proposition that precipitation responds more to cyclical variations in solar activity than to anything else.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/p/precipasia.php>.

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#### 4.3.4. Europe

##### 4.3.4.1. Central

Koning and Franses (2005) conducted a detailed analysis of a century of daily precipitation data that had been acquired at the de Bilt meteorological station in the Netherlands. Using what they call "robust nonparametric techniques," they found that the cumulative distribution function of annual maximum precipitation levels remained constant throughout the period 1906-2002, leading them to conclude that "precipitation levels are not getting higher." In addition, they report that similar analyses they performed for the Netherlands' five other meteorological stations "did not find qualitatively different results."

Moving eastward, and extending the temporal domain of study from one century to five, Wilson *et al.* (2005) developed two versions of a March-August precipitation chronology based on living and historical tree-ring widths obtained from the Bavarian Forest of southeast Germany for the period 1456-2001. The first version, standardized with a fixed 80-year spline function (SPL), was designed to retain decadal and higher frequency variations, while the second version used regional curve standardization (RCS) to retain lower frequency variations. Their efforts revealed significant yearly and decadal variability in the SPL chronology; but there did not appear to be any trend toward either wetter or drier conditions over the 500-year period. The RCS reconstruction, on the other hand, better captured lower frequency variation, suggesting that March-August precipitation was substantially greater than the long-term average during the periods 1730-1810 and 1870-2000 and drier than the long-term average during the periods 1500-1560, 1610-1730 and 1810-1870. Once again, however, there was little evidence of a long-term trend.

Moving still further east in Central Europe, and covering a full millennium and a half, Solomina *et al.* (2005) derived the first tree-ring reconstruction of spring (April-July) precipitation for the Crimean peninsula, located on the northern coast of the Black Sea in the Ukraine, for the period 1620-2002, after which they utilized this chronology to correctly date and correlate with an earlier precipitation reconstruction derived from a sediment core taken in 1931 from nearby Saki Lake, thus ending up with a proxy precipitation record for the region that stretched all the way back to AD 500. In describing their findings, Solomina *et al.* say that no trend in precipitation was evident over the period 1896-1988 in an instrumental record obtained at a

location adjacent to the tree-sampling site. Also, the reconstructed precipitation values from the tree-ring series revealed year-to-year and decadal variability, but remained "near-average with relatively few extreme values" from about the middle 1700s to the early 1800s and again since about 1920. The most notable anomaly of the 1500-year reconstruction was an "extremely wet" period that occurred between AD 1050 and 1250, which Solomina *et al.* describe as broadly coinciding with the Medieval Warm Epoch, when humidity was higher than during the instrumental era.

The results of these several analysis demonstrate that over the period of 20th-century global warming -- which climate alarmists claim was *unprecedented over the past two millennia or more* -- the climate-model-based expectation of enhanced precipitation was not observed in Central Europe. Of course, Central Europe represents but a small portion of the entire planet. Nevertheless, for a warming that was supposedly so extreme, one would have expected to have seen *something* along the lines of what the alarmists have claimed would be the case ... if they were correct. *But we don't!* And perhaps the reason *why* we don't see what they predict is that earth's climate is likely not yet as warm as it was during the Medieval Warm Period, when the data of Solomina *et al.* suggest that the region they studied *was* distinctly wetter than it was both before and after that time, and when, of course, the air's CO<sub>2</sub> concentration was fully 100 ppm *less* than it is today.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/p/precipeurope.php>.

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### 4.3.4.2. Mediterranean

Starting at the western extreme of the continent, Rodrigo *et al.* (2001) used a variety of documentary data to reconstruct seasonal rainfall in Andalusia (southern Spain) from 1501 to 1997, after which they developed a relationship between seasonal rainfall and the North Atlantic Oscillation (NAO) over the period 1851-1997, which they used to reconstruct a history of the NAO from 1501 to 1997. This work revealed that the NAO influence on climate is stronger in winter than in other seasons of the year in Andalusia, explaining 40% of the total variance in precipitation; and Rodrigo *et al.* make a point of noting that "the recent positive temperature anomalies over western Europe and recent dry [*not wet*] winter conditions over

southern Europe and the Mediterranean are strongly related to the persistent and exceptionally strong positive phase of the NAO index since the early 1980s," as opposed to an intensification of global warming.

Also working in the Andalusia region of southern Spain, Sousa and Garcia-Murillo (2003) studied proxy indicators of climatic change in Doñana Natural Park over a period of several hundred years, comparing their results with those of other such studies conducted in neighboring regions. This work revealed that the Little Ice Age (LIA) was by no means uniform in their region of study, as it included both wetter and drier periods. Nevertheless, they cite Rodrigo *et al.* (2000) as indicating that "the LIA was characterized in the southern Iberian Peninsula by increased rainfall," and they cite Grove (2001) as indicating that "climatic conditions inducing the LIA glacier advances [of Northern Europe] were also responsible for an increase in flooding frequency and sedimentation in Mediterranean Europe." Sousa and Garcia-Murillo's work complements these findings by indicating "an aridization of the climatic conditions after the last peak of the LIA (1830-1870)," which suggests that much of Europe became drier, not wetter, as the earth recovered from the global chill of the Little Ice Age.

Moving eastward into Italy, Crisci *et al.* (2002) analyzed rainfall data collected from 81 gauges spread throughout the Tuscany region for three different periods: (1) from the beginning of each record through 1994, (2) the shorter 1951-1994 period, and (3) the still-shorter 1970-1994 period. For each of these periods, trends were derived for extreme rainfall durations of 1, 3, 6, 12 and 24 hours. This work revealed that for the period 1970-1994, the majority of all stations exhibited no trends in extreme rainfall at any of the durations tested; while four had positive trends at all durations and none had negative trends at all durations. For the longer 1951-1994 period, the majority of all stations exhibited no trends in extreme rainfall at any of the durations tested; while none had positive trends at all durations and only one had negative trends at all durations. For the still-longer complete period of record, the majority of all stations again continued to exhibit no trends in extreme rainfall at any of the durations tested; while none had positive trends at all durations and only one had negative trends at all durations, revealing no impact of 20th-century global warming one way or the other.

Working in northern Italy, Tomozeiu *et al.* (2002) performed a series of statistical tests to investigate the nature and potential causes of trends in winter (Dec-Feb) mean precipitation recorded at forty stations over the period 1960-1995. This work revealed that nearly all of the stations experienced significant *decreases* in winter precipitation over the 35-year period of study; and by subjecting the data to a Pettitt test, they detected a significant downward shift at all stations around 1985. An Empirical Orthogonal Function analysis was also performed on the precipitation data, revealing a principal component that represented a common large-scale process that was likely responsible for the phenomenon. Strong correlation between this component and the North Atlantic Oscillation (NAO) suggested, in their words, that the changes in winter precipitation around 1985 "could be due to an intensification of the positive phase of the NAO." In this case, therefore, there was not only no *increase* in precipitation over the period of time when climate alarmists claim the planet warmed at a rate that was *unprecedented over the past two millennia*, there was an actual *decrease*, which not only had



nothing to do with global warming but was more likely the result of a simple regime shift of the NAO.

Working in the eastern Basilicata region of southern Italy, where they concentrated on characterizing trends in extreme rainfall events, as well as resultant flood events and landslide events, Clark and Rendell (2006) analyzed 50 years of rainfall records (1951-2000). This work indicated, in their words, that "the frequency of extreme rainfall events in this area declined by more than 50% in the 1990s compared to the 1950s." In addition, they report that "impact frequency also decreased, with landslide-event frequency changing from 1.6/year in the period 1955-1962 to 0.3/year from 1985 to 2005, while flood frequency peaked at 1.0/year in the late 1970s before declining to less than 0.2/year from 1990." Hence, they concluded that if the climate-driven changes they observed over the latter part of the 20th century continue, "the landscape of southern Italy and the west-central Mediterranean will become increasingly stable," or as they say in their concluding paragraph, "increased land-surface stability will be the result."

Continuing westward to Bulgaria, Alexandrov *et al.* (2004) analyzed a number of 20th-century data sets from throughout the country, finding "a decreasing trend in annual and especially summer precipitation from the end of the 1970s" and that "variations of annual precipitation in Bulgaria showed an overall decrease." In addition, they report that the region stretching from the Mediterranean into European Russia and the Ukraine "has experienced decreases in precipitation by as much as 20% in some areas."

Last of all, based on analyses of tree-ring width data and their connection to large-scale atmospheric circulation, Touchan *et al.* (2005) developed summer (May-August) precipitation reconstructions for several parts of the eastern Mediterranean region, including Turkey, Syria, Lebanon, Cyprus and Greece, which extend back in time as much as 600 years. Over this period, they found that May-August precipitation varied on multi-annual and decadal timescales, but that on the whole there were no long-term trends. The longest dry period occurred in the late 16th century (1591-1595), while there were two extreme wet periods: 1601-1605 and 1751-1755. In addition, both extreme wet and dry precipitation events were found to be more variable over the intervals 1520-1590, 1650-1670 and 1850-1930, indicating that as the globe experienced the supposedly unprecedented warming of the last decades of the 20th century, May-August precipitation in the eastern Mediterranean region actually become *less* variable than it had been in the earlier part of the century.

In conclusion, the story told by these several studies of precipitation characteristics of Mediterranean Europe is vastly different from that which is routinely claimed for the planet as a whole by the world's climate alarmists.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/p/precipeuropemed.php>.

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#### 4.3.4.3. Northern

Out in the middle of the North Atlantic Ocean in Iceland, Hanna *et al.* (2004) analyzed variations in several climatic variables, including precipitation, over the past century in an effort to determine if there is "possible evidence of recent climatic changes" in that cold island nation. For the period 1923-2002, precipitation appeared to have increased slightly, although they questioned the veracity of the trend, citing several biases that may have corrupted the data base.

Back on the mainland, Linderholm and Molin (2005) analyzed two independent precipitation proxies, one derived from tree-ring data and one from a farmer's diary, to produce a 250-year record of summer (June-August) precipitation in east central Sweden. This work revealed there had been a high degree of variability in summer precipitation on inter-annual to decadal time scales throughout the record. Over the past century of supposedly unprecedented global warming, however, precipitation was found to have exhibited *less* variability than it did during the 150 years that preceded it.

Finally, in a study covering the longest time span of all, Linderholm and Chen (2005) derived a 500-year winter (September-April) precipitation chronology from tree-ring data obtained within the northern boreal forest zone of west-central Scandinavia in an effort to better understand historic precipitation variability within this region. The reconstructed chronology they developed showed considerable variability, with the exception of a fairly stable period of above-average precipitation between AD 1730 and 1790. Additionally, above average winter precipitation was found to have occurred in 1520-1561, 1626-1647, 1670-1695, 1732-1851, 1872-1892 and 1959 to the present, with the highest values reported in the early to mid-1500s; while below average winter precipitation was observed during 1504-1520, 1562-1625, 1648-1669, 1696-1731, 1852-1871, and 1893-1958, with the lowest values occurring at the beginning of the record and the beginning of the 17th century. These findings thus demonstrated that non-CO<sub>2</sub>-forced wetter and drier conditions than those of the present have occurred repeatedly within this region throughout the past five centuries, and that similar extreme conditions may therefore be expected to *naturally* recur in the future.

In considering these diverse observations from Northern Europe, it is clear they provide no support whatsoever for alarmist claims of imminent changes in precipitation characteristics outside the bounds of historic variability.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/p/precipeuopenorth.php>.

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#### 4.3.5. United States

Climate models typically suggest that global warming will adversely affect water resources via changes in rainfall amounts and intensities. As noted by Kunkel (2003), for example, "several studies have argued that increasing greenhouse gas concentrations will result in an increase of heavy precipitation (Cubasch *et al.*, 2001; Yonetani and Gordon, 2001; Kharin and Zwiers, 2000; Zwiers and Kharin, 1998; Trenberth, 1998)." Consequently, in an effort to either substantiate or reject this hypothesis, numerous scientists are examining historical and proxy precipitation records to see what effect the temperature increase of the Little Ice Age-to-Modern Warm Period transition might have had on earth's hydrologic cycle. In this section, we review what several researchers have learned in this regard about precipitation in the heart of North America, i.e., the United States, as they have sought to determine if there have been any dangerous increases in the intensity and frequency of extreme precipitation events in this particular part of the world.

Molnar and Ramirez (2001) conducted a detailed watershed-based analysis of precipitation and streamflow trends for the period 1948-97 in the semiarid region of the Rio Puerco Basin of New Mexico. They found, in their words, that "at the annual timescale, a statistically significant increasing trend in precipitation in the basin was detected." This trend was driven primarily by an increase in the number of rainy days in the moderate rainfall intensity range, with essentially no change being observed at the high-intensity end of the spectrum. In the case of streamflow, however, there was *no* trend at the annual timescale; but monthly totals *increased* in *low*-flow months and *decreased* in *high*-flow months.

What are the implications of these observations? Increasing precipitation in a semiarid region sounds like a huge plus to us; and having most of that increase in the moderate rainfall intensity range also sounds like a plus. Increasing streamflow in *low*-flow months sounds good as well, as does decreasing streamflow in *high*-flow months. In fact, what more could one possibly desire in terms of changes in precipitation? ... especially in a world that climate alarmists claim is supposed to be experiencing more extreme weather events and increases in both floods and droughts?

We once thought that this prediction was a clever ploy on the part of the world's climate alarmists, i.e., that by predicting more warming-induced floods and droughts *at one and the same time*, they were making sure there was no way they could possibly miss in their predictions of CO<sub>2</sub>-induced calamities. It would appear, however, that we were *wrong* in that assumption: *they did miss!*

In a much colder part of the country, Cowles *et al.* (2002) analyzed *snow water equivalent* (SWE) data obtained from four different measuring systems -- snow courses, snow telemetry,

aerial markers and airborne gamma radiation -- at more than 2000 sites in the eleven westernmost states over the period 1910-1998. This work revealed that the long-term SWE trend of this entire region was *negative*, but with some significant within-region differences. In the northern Rocky Mountains and Cascades of the Pacific Northwest, for example, the trend was decidedly negative, with SWE decreasing at a rate of 0.1 to 0.2 inches per year. In the intermountain region and southern Rockies, however, there was *no* change in SWE with time. Cowles *et al.* additionally note that their results "reinforce more tenuous conclusions made by previous authors," citing Chagnon *et al.* (1993) and McCabe and Legates (1995), who studied snow course data from 1951-1985 and 1948-1987, respectively, at 275 and 311 sites. They too found a decreasing trend in SWE at most sites in the Pacific Northwest but more ambiguity in the southern Rockies.

These findings are particularly interesting in light of the fact that nearly all climate models suggest the planet's hydrologic cycle will be *enhanced* in a warming world and that precipitation will *increase*. This prediction is especially applicable to the Pacific Northwest of the United States, where Kusnierczyk and Ettl (2002) report that climate models predict "increasingly warm and wet winters," as do Leung and Wigmosta (1999). Over the period of Cowles *et al.*'s study, however, when there was well-documented worldwide warming, precipitation that fell and accumulated as snow in the western USA did not respond as predicted. In fact, over the Pacific Northwest, it did just the *opposite*.

Garbrecht and Rossel (2002) used state divisional monthly precipitation data from the US National Climatic Data Center to investigate the nature of precipitation throughout the US Great Plains from January 1895 through December 1999, finding that regions in the central and southern Great Plains experienced above-average precipitation over the last two decades of the 20th century. This 20-year span of time was the longest and most intense wet period of the entire 105 years of record, and was primarily the result of a reduction in the number of dry years and an increase in the number of wet years. What made it even better was the fact that the number of *very wet* years, in the words of the authors, "did not increase as much and even showed a decrease for many regions." The northern and northwestern Great Plains also experienced a precipitation increase at the end of this 105-year interval, but it was primarily confined to the final decade of the 20th century; and again, as Garbrecht and Rossel report, "fewer dry years over the last 10 years, as opposed to an increase in very wet years, were the leading cause of the observed wet conditions."

It is interesting to note, in this regard, that during the period of time described by the alarmists as having been host to the most dramatic global warming of the past two *millennia*, which according to them should have resulted in devastating droughts and floods, the Great Plains of the United States, like the Rio Puerco Basin of New Mexico, actually experienced the best of both water-resource worlds. Overall, conditions got wetter, which means less drought; while the constancy - or even *decline* - in the number of *very wet* years tended to mitigate against floods. What could possibly be better? It looks like the new Modern Warm Period is going to eventually be classified as another Little Climatic *Optimum!*

Taking a look at the entire conterminous United States from 1895-1999, McCabe and Wolock (2002) evaluated and analyzed (1) values of annual precipitation minus annual potential evapotranspiration, (2) surplus water that eventually becomes streamflow, and (3) the water deficit that must be supplied by irrigation to grow vegetation at an optimum rate. Their work revealed that for the country as a whole, there was a statistically significant increase in the first two of these three parameters, while for the third there was no change. In describing the significance of these findings, McCabe and Wolock say "there is concern that increasing concentrations of atmospheric carbon dioxide and other radiatively active gases may cause global warming and ... adversely affect water resources." The results of their analyses, however, reveal that over the past century of significant (but neither unusual nor unnatural) global warming, just the *opposite* has occurred, at least within the conterminous United States: moisture has become *more* available, while there has been no change in the amount of water required for optimum plant growth.

Also studying the conterminous United States were Kunkel *et al.* (2003), who analyzed a new data base of daily precipitation observations for the period 1895-2000. This effort indicated, in their words, that "heavy precipitation frequencies were relatively high during the late 19th/early 20th centuries, decreasing to a minimum in the 1920s and 30s, followed by a general increase into the 1990s." More specifically, they note that "for 1-day duration events, frequencies during 1895-1905 are comparable in magnitude to frequencies in the 1980s and 1990s," while "for 5- and 10-day duration events, frequencies during 1895-1905 are only slightly smaller than late 20th century values."

In commenting on these findings, Kunkel *et al.* note that since enhanced greenhouse gas forcing of the climate system was very small in the early years of this record, the elevated extreme precipitation frequencies of that time "were most likely a consequence of naturally forced variability," which further suggests, in their words, "the possibility that natural variability could be an important contributor to the recent increases." This is also the conclusion of Kunkel (2003), who in a review of this and other pertinent studies states that frequencies of extreme precipitation events in the United States in the late 1800s and early 1900s "were about as high as in the 1980s/1990s." Consequently, he too concludes that "natural variability in the frequency of precipitation extremes is quite large on decadal time scales and cannot be discounted as the cause or one of the causes of the recent increases."

Working with proxy data that extend much further back in time, Haston and Michaelsen (1997) developed a 400-year history of precipitation for 29 stations in coastal and near-interior California between San Francisco Bay and the U.S.-Mexican border using tree-ring chronologies. Their research revealed that although region-wide precipitation during the 20th century was higher than what was experienced during the preceding three centuries, it was also "less variable compared to other periods in the past," both of which characteristics are huge positive developments for both man and nature in this important region of California.

In a similar study, Gray *et al.* (2003) examined fifteen tree ring-width series that had been used in previous reconstructions of drought for evidence of low-frequency variation in precipitation

in five regional composite chronologies pertaining to the central and southern Rocky Mountains. In describing what they found, they say that "strong multidecadal phasing of moisture variation was present in all regions during the late 16th century megadrought," and that "oscillatory modes in the 30-70 year domain persisted until the mid-19th century in two regions, and wet-dry cycles were apparently synchronous at some sites until the 1950s drought." They also note that "severe drought conditions across consecutive seasons and years in the central and southern Rockies may ensue from coupling of the cold phase PDO [Pacific Decadal Oscillation] with the warm phase AMO [Atlantic Multidecadal Oscillation] (Cayan *et al.*, 1998; Barlow *et al.*, 2001; Enfield *et al.*, 2001)," something they envision happening in both the severe drought of the 1950s and the late 16th-century megadrought. Hence, there is no particular reason to associate any of the wetter or drier periods of the 20th century with global warming, for both conditions appear to be naturally recurring products of various climate "regime shifts" in the Pacific and Atlantic Oceans that are independent of the mean thermal state of the planet.

Going back even further in time, Ni *et al.* (2002) developed a 1000-year history of cool-season (November-April) precipitation for each climate division in Arizona and New Mexico from a network of 19 tree-ring chronologies. With respect to drought, they found that "sustained dry periods comparable to the 1950s drought" occurred in "the late 1000s, the mid 1100s, 1570-97, 1664-70, the 1740s, the 1770s, and the late 1800s." They also note that the 1950s drought "was large in scale and severity, but it only lasted from approximately 1950 to 1956," whereas the 16th century megadrought lasted more than four times longer. With respect to the opposite of drought, Ni *et al.* report that several wet periods comparable to the wet conditions seen in the early 1900s and after 1976 occurred in "1108-20, 1195-1204, 1330-45, the 1610s, and the early 1800s." They also note that "the most persistent and extreme wet interval occurred in the 1330s."

Speaking of the *causes* of the different precipitation extremes, Ni *et al.* say that "the 1950s drought corresponds to La Niña/-PDO [Pacific Decadal Oscillation] and the opposite polarity [+PDO] corresponds to the post-1976 wet period," which leads them to hypothesize that "the prominent shifts seen in the 1000 year reconstructions in Arizona and New Mexico may also be linked to strong shifts of the coupled ENSO-PDO system." For the particular part of the world covered by their study, therefore, there appears to be nothing unusual about the extremes of both wetness and dryness experienced during the 20th century.

In another equally long study, but on the opposite side of the country, Cronin *et al.* (2000) measured and analyzed salinity gradients across sediment cores extracted from Chesapeake Bay, the largest estuary in the United States, in an effort to examine precipitation variability in the surrounding watershed over the past 1000 years. They found a high degree of decadal and multidecadal variability between wet and dry conditions throughout the record, where regional precipitation totals fluctuated between 25 to 30%, often in "extremely rapid [shifts] occurring over about a decade." Precipitation over the last two centuries, however, was on average greater than what it was during the previous eight centuries, with the exception of the Medieval Warm Period (AD 1250-1350), when the climate was judged to have been "extremely

wet." In addition, it was determined that this region, like the southwestern United States, had experienced several "mega-droughts," lasting from 60-70 years in length, some of which Cronin *et al.* describe as being "more severe than twentieth century droughts."

Also like the study of Ni *et al.*, Cronin *et al.*'s work reveals nothing unusual about precipitation during the 20th century, the latter two decades of which climate alarmists adamantly claim comprise the warmest such period of the past *two millennia*. It indicates, for example, that both wetter and drier intervals occurred repeatedly in the past in the Chesapeake Bay watershed; and there is no reason not to believe they will occur in the future ... with or without any further global warming. Consequently, there is no basis in real-world data for predicting warming-induced droughts and floods in this and other parts of the world.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/p/precipusa.php>.

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#### 4.3.6. Canada and Mexico

Kunkel (2003) reports that "several studies have argued that increasing greenhouse gas concentrations will result in an increase of heavy precipitation (Cubasch *et al.*, 2001; Yonetani and Gordon, 2001; Kharin and Zwiers, 2000; Zwiers and Kharin, 1998; Trenberth, 1998)." Consequently, Kunkel looked for such a signal in precipitation data from Canada that covered much of the past century. His search, however, was in vain, as the data indicated, in his words, that "there has been no discernible trend in the frequency of the most extreme events in Canada."

Zhang *et al.* (2001) also studied the temporal characteristics of heavy precipitation events across Canada, using what they describe as "the most homogeneous long-term dataset currently available for Canadian daily precipitation." Their efforts revealed that decadal-scale variability was a dominant feature of both the frequency and intensity of the annual number of extreme precipitation events, but they found "no evidence of any significant long-term changes." When the annual data were divided into seasonal data, however, an increasing trend in the number of extreme autumn *snowfall* events was noted; and an investigation into precipitation totals (extreme plus non-extreme events) revealed a slightly increasing trend that was attributed to increases in the number of *non-heavy* precipitation events. Zhang *et al.*'s overall conclusion, therefore, was that "increases in the concentration of atmospheric greenhouse gases during the twentieth century have not been associated with a generalized increase in extreme precipitation over Canada."

Taking a longer view of the subject was Lamoureaux (2000), who analyzed varved lake sediments obtained from Nicolay Lake, Cornwall Island, Nunavut, Canada, and compared the results with rainfall events recorded at a nearby weather station over the period 1948-1978, which comparison enabled the reconstruction of a rainfall history for the location over the 487-year period from 1500 to 1987. This history was suggestive of a small, but statistically insignificant, increase in total rainfall over the course of the record. *Heavy* rainfall was most frequent during the 17th and 19th centuries, which were the *coldest* periods of the past 400 years in the Canadian High Arctic, as well as the Arctic as a whole. In addition, Lamoureaux says that "more frequent extremes and increased variance in yield occurred during the 17th and 19th centuries, likely due to increased occurrences of cool, wet synoptic types during the coldest periods of the Little Ice Age."

This study, like the others discussed above, contradicts the climate-alarmist claim that extreme precipitation events become more frequent and more severe with increasing temperature. Here in the Canadian High Arctic, in a part of the planet predicted to be most impacted by CO<sub>2</sub>-induced global warming, rising temperatures have been shown to *reduce* precipitation extremes, even in the face of a slight increase in total precipitation.

South of the United States, Diaz *et al.* (2002) created a 346-year history of winter-spring (November-April) precipitation for the Mexican state of Chihuahua, based on earlywood width chronologies of over 300 Douglas fir trees growing at four locations along the western and southern borders of Chihuahua and at two locations in the United States just above Chihuahua's northeast border. This exercise revealed, in their words, that "three of the 5 worst winter-spring drought years in the past three-and-a-half centuries are estimated to have occurred during the 20th century." Although this fact makes it *sound* like the 20th century was highly anomalous in this regard, *it was not*; for two of those three worst drought years occurred during a decadal period of average to slightly-above-average precipitation, so the three years were *not* representative of long-term droughty conditions.

Diaz *et al.* additionally report that "the longest drought indicated by the smoothed reconstruction lasted 17 years (1948-1964)," which again makes the 20th century look unusual in this regard. However, for several of the years of that interval, precipitation values were only *slightly* below normal; and there were four very similar dry periods interspersed throughout the preceding two and a half centuries: one in the late 1850s and early 1860s, one in the late 1790s and early 1800s, one in the late 1720s and early 1730s, and one in the late 1660s and early 1670s.

With respect to the 20th century alone, there was a long period of high winter-spring precipitation that stretched from 1905 to 1932; and following the major drought of the 1950s, precipitation remained at, or just slightly above, normal for the remainder of the record. Finally, with respect to the entire 346 years, *there was no long-term trend in the data, nor was there any evidence of a significant departure from that trend over the course of the 20th century.* Consequently, Chihuahua's precipitation history did not differ in any substantial way during the 20th century from what it was over the prior *quarter of a millennium*, suggesting that neither 20th-century anthropogenic CO<sub>2</sub> emissions nor 20th-century warming - whether natural or human-induced - significantly impacted precipitation in that part of North America.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/p/precipnortham.php>.

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#### 4.3.7. Global

Huntington (2006) notes there is "a theoretical expectation that climate warming will result in increases in evaporation and precipitation, leading to the hypothesis that one of the major consequences will be an intensification (or acceleration) of the water cycle (DelGenio *et al.*, 1991; Loaciga *et al.*, 1996; Trenberth, 1999; Held and Soden, 2000; Arnell *et al.*, 2001)," and in reviewing the scientific literature on *precipitation*, he concludes that on a globally averaged basis, "precipitation over land increased by about 2% over the period 1900-1998 (Dai *et al.*, 1997; Hulme *et al.*, 1998)."

New *et al.* (2001) also reviewed several global precipitation data sets, analyzing the information they contain to obtain a picture of precipitation *patterns* over the 20th century. In their case, they determined that precipitation over the land area of the globe was mostly below the century-long mean over the first decade and a half of the record, but that it increased from 1901 to the mid-1950s, whereupon it remained above the century-long mean until the 1970s,

after which it declined by about the same amount to 1992 (taking it well below the century-long mean), whereupon it recovered and edged upward towards the century mean. Hence, for the entire century, there was indeed a *slight* increase in global land area precipitation; but *since 1915* there was essentially *no net change*.

For the *oceanic* portion of the world between 30°N and 30°S, however, the record of which begins in 1920, there *was* a discernable change in precipitation over the course of the record; however, it was an overall *decrease* of about 0.3% per decade. Hence, *for the world as a whole*, which is 70% covered by water, there may well have been a slight *decrease* in precipitation since about 1917 or 18.

Concentrating on the last half of the 20th century, Neng *et al.* (2002) analyzed data from 1948 to 2000 in a quest to determine the effect of warm ENSO years on annual precipitation over the land area of the globe. In doing so, they found that some regions experienced *more* rainfall in warm ENSO years, while others experienced *less*. However, in the words of the researchers, "in warm event years, the land area where the annual rainfall was reduced is *far greater* [our italics] than that where the annual rainfall was increased, and the reduction is *more significant* [our italics] than the increase." Consequently, whereas state-of-the-art climate models nearly always *predict* more precipitation in a warming world, the data of Neng *et al.*'s study *depict* just the *opposite* effect over the land area of the globe. Hence, with respect to one of the most basic of all climate-model predictions, there appears to be a total lack of vindication in the real world, where it really counts.

Most recently - and noting that "the Global Precipitation Climatology Project (GPCP) has produced merged satellite and in situ global precipitation estimates, with a record length now over 26 years beginning 1979 (Huffman *et al.*, 1997; Adler *et al.*, 2003)" - Smith *et al.* (2006) used empirical orthogonal function (EOF) analysis to study annual GPCP-derived precipitation variations over the period of record. In doing so, they found that the first three EOFs accounted for 52% of the observed variance in the precipitation data. Mode 1 was associated with mature ENSO conditions and correlated strongly with the Southern Oscillation Index, while Mode 2 was associated with the strong warm ENSO episodes of 1982/83 and 1997/98. Mode 3, on the other hand, was uncorrelated with ENSO but was associated with tropical trend-like changes that were correlated with interdecadal warming of tropical sea surface temperatures.

*Globally*, Smith *et al.* report that "the mode 3 variations average to near zero, so this mode does not represent any net change in the amount of precipitation over the analysis period." Consequently, over the period 1979-2004, when alarmists claim the world warmed at a rate and to a degree that was *unprecedented over the past two millennia*, Smith *et al.* found that most of the precipitation variations in their global data set were "associated with ENSO and have no trend." As for the variations that were *not* associated with ENSO and that *did* exhibit trends, they say that the trends were associated "with increased tropical precipitation over the Pacific and Indian Oceans associated with local warming of the sea." However, they note that this increased precipitation was "balanced by decreased precipitation in other regions," so that "the global average change [was] near zero."

Over the earth as a whole, therefore, it would appear from Smith *et al.*'s study, as well as from the other studies described above, that one of the major theoretical expectations of the climate modeling community remains unfulfilled, even under the supposedly highly favorable thermal conditions of the last quarter-century, which observation suggests that their other major theoretical expectation, i.e., catastrophic CO<sub>2</sub>-induced global warming, will likely remain unfulfilled too.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/p/precipglobal.php>.

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#### **4.4. Streamflow**

Model projections suggest that CO<sub>2</sub>-induced global warming will adversely impact earth's water resources by inducing large changes in global streamflow characteristics. As a result, many scientists are examining proxy streamflow records in an effort to determine how temperature changes of the 20th century may or may not have impacted this aspect of the planet's hydrologic cycle. We here review such findings for North America and Eurasia, seeking to discover if there have indeed been any 20th-century changes in streamflow regimes that might reasonably have been caused by 20th-century changes in air temperature and atmospheric CO<sub>2</sub> concentration, which latter changes are frequently characterized as having been unprecedented (or nearly so) over *the past thousand years*. We begin with a study of records from Eurasia.

Additional information on this topic, including reviews on streamflow not discussed here, can be found at [http://www.co2science.org/subject/s/subject\\_s.php](http://www.co2science.org/subject/s/subject_s.php) under the heading Streamflow.

##### **4.4.1. Eurasia**

Pederson *et al.* (2001) used tree-ring chronologies from northeastern Mongolia to develop annual precipitation and streamflow histories for the period 1651-1995. This work revealed, with respect to both standard deviations and 5-year intervals of extreme wet and dry periods, that "variations over the recent period of instrumental data are not unusual relative to the prior record," although they say that the reconstructions "appear to show more frequent extended wet periods in more recent decades." Nevertheless, they state that this observation "does not demonstrate unequivocal evidence of an increase in precipitation as suggested by some climate models." Spectral analysis of the data also revealed significant periodicities of 12 and 20-24

years, suggesting, in the researchers' words, "possible evidence for solar influences in these reconstructions for northeastern Mongolia."

Working in another part of the same region, Davi *et al.* (2006) report that "absolutely dated tree-ring-width chronologies from five sampling sites in west-central Mongolia were used in precipitation models and an individual model was made using the longest of the five tree-ring records (1340-2002)," which effort led to a reconstruction of streamflow that extended from 1637 to 1997. In analyzing these data, the four researchers discovered there was "much wider variation in the long-term tree-ring record than in the limited record of measured precipitation," which for the region they studied covered the period from 1937 to 2003. In addition, they report their streamflow history indicates that "the wettest 5-year period was 1764-68 and the driest period was 1854-58," while "the most extended wet period [was] 1794-1802 and ... extended dry period [was] 1778-83." For this part of Mongolia, therefore - which the researchers say "is representative of the central Asian region" - there is no support to be found for the climate-alarmist contention that the "unprecedented" warming of the 20th century has led to increased variability in precipitation and streamflow.

Pekarova *et al.* (2003) analyzed the annual discharge rates of selected large rivers of the world for recurring cycles of wet and dry periods. For those rivers with sufficiently long and accurate data series, they also derived long-term discharge rate *trends*. This latter analysis, however, did not show "any significant trend change in long-term discharge series (1810-1990) in representative European rivers," including the Goeta, Rhine, Neman, Loire, Wesaer, Danube, Elbe, Oder, Vistule, Rhone and Po. These latter observations are most interesting, for they indicate that even over the 180-year time period that saw the demise of the Little Ice Age and the ushering in of the Current Warm Period, there were no long-term trends in the discharge rates of the major rivers of Europe.

In another study, Hisdal *et al.* (2001) performed a series of statistical analyses on more than 600 daily streamflow records from the European Water Archive to examine trends in the severity, duration and frequency of drought over the following four time periods: 1962-1990, 1962-1995, 1930-1995, and 1911-1995. This protocol indicated that "despite several reports on recent droughts in Europe, there is no clear indication that streamflow drought conditions in Europe have generally become more severe or frequent in the time periods studied." Quite to the contrary, they report discovering that the number of trends pointing towards decreasing streamflow deficits or fewer drought events exceeded the number of trends pointing towards increasing drought deficits or more drought events.

Looking back towards Asia, Cluis and Laberge (2001) utilized streamflow records stored in the databank of the Global Runoff Data Center at the Federal Institute of Hydrology in Koblenz (Germany) to see if there were any recent changes in river runoff of the type predicted by IPCC scenarios of global warming, such as increased streamflow and increases in streamflow variability that would lead to more floods and droughts. *Spatially*, their study encompassed 78 rivers said to be "geographically distributed throughout the whole Asia-Pacific region," while



*temporally* the mean start and end dates of the river flow records were  $1936 \pm 5$  years and  $1988 \pm 1$  year.

As a result of their analyses, the two researchers determined that *mean* river discharges were unchanged in 67% of the cases investigated; and where trends did exist 69% of them were downward. Likewise, *maximum* river discharges were unchanged in 77% of the cases investigated; and where trends did exist 72% of them were downward. *Minimum* river discharges, on the other hand, were unchanged in 53% of the cases investigated; while where trends did exist 62% of them were *upward*.

With respect to the implications of these findings, we note that in the case of *mean* river discharge, the empirical observations go doubly against climate-alarmist predictions, i.e., most rivers show no change in flow volume, while most of those that do show changes exhibit decreases. In the case of *maximum* river discharge, the empirical observations also go doubly against climate-alarmist predictions, i.e., most rivers show no change in flow volume, while most of those that do exhibit changes show decreases, indicative of the likelihood of *less flooding*. Finally, in the case of *minimum* river discharge, the empirical observations once again go doubly against climate alarmist predictions, i.e., most rivers show no change in flow volume, while most of those that do exhibit changes show increases, indicative of the likelihood of *less drought*. Consequently, out of six possible metrics related to streamflow trends, all six exhibit changes that are contrary to IPCC-promoted scenarios of climate change.

In another study, MacDonald *et al.* (2007) used "tree ring records from a network of sites extending across northern Eurasia to provide reconstructions [extending back to AD 1800] of annual discharge for the October to September water year for the major Eurasian rivers entering the Arctic Ocean (S. Dvina, Pechora, Ob', Yenisey, Lena, and Kolyma)." Results indicated that annual discharges of the mid to late 20th century previously reported are not significantly greater than discharges experienced over the preceding 200 years, and "are thus still within the range of long-term natural variability." In addition, they say their "longer-term discharge records do not indicate a consistent positive significant correlation between discharge [and] Siberian temperature." In fact, they report there are actually weak *negative* correlations between discharge and temperature on some of the rivers over the period of their study.

In a contemporaneous study, Smith *et al.* (2007) present "a first analysis of a new data set of daily discharge records from 138 small to medium-sized unregulated rivers in northern Eurasia," focusing on providing "a first continental-scale assessment of low-flow trends since the 1930s." Results indicate that "a clear result of this analysis is that, on balance, the monthly minimum values of daily discharge, or 'low flows,' have risen in northern Eurasia during the 20th century," adding that "from 12 unusually complete records from 1935-2002 we see that the minimum flow increases are greatest since ~1985."

From the things discovered by Smith *et al.*, therefore, it is clear that over much of northern Eurasia, predictions of more drought seem rather off the mark, as daily low flows of the

majority of northern Eurasian rivers have been *increasing*. Moreover, in the words of the five researchers, they have been increasing "in summer as well as winter and in non-permafrost as well as permafrost terrain," with the greatest increases occurring "since ~1985," when the world experienced what climate alarmists typically describe as a warming that was *unprecedented* over the past one to two *millennia*.

Writing about the Qinghai-Tibet Plateau, where they conducted their streamflow study, Cao *et al.* (2006) note that "both theoretical arguments and models suggest that net high-latitude precipitation increases in proportion to increases in mean hemispheric temperature (Houghton *et al.*, 2001; Rahmstorf and Ganopolski, 1999; Bruce *et al.*, 2002)," stating that in these scenarios "under global warming, mainly in the middle and west regions of northwest China, precipitation increases significantly," so that "some researchers [have] even advanced the issue of [a] climatic shift from warm-dry to warm-wet in northwest China (Shi, 2003)," with the ultimate expectation that total river discharge within the region would significantly increase in response to global warming.

As a test of these climate-model predictions, Cao *et al.* analyzed annual discharge data for five large rivers of the Qinghai-Tibet Plateau over the period 1956-2000, using the Mann-Kendall nonparametric trend test; and in doing so, they found that over the period of their study, "river discharges in the Qinghai-Tibet Plateau, in general, have no obvious change with the increase of the Northern Hemisphere surface air temperature." Hence, because they could detect, in their words, "no increase in the stream discharge in the Qinghai-Tibet Plateau with global warming," Cao *et al.* concluded that their real-world findings are not "in accordance with the anticipated ideas" that led them to conduct their study. Indeed, the disconnect between streamflow and global warming in this and many other studies argues strongly against either (1) the claimed *consequences* of global warming or (2) the claimed *large magnitude* of global warming or (3) *both* of these standard climate-alarmist claims.

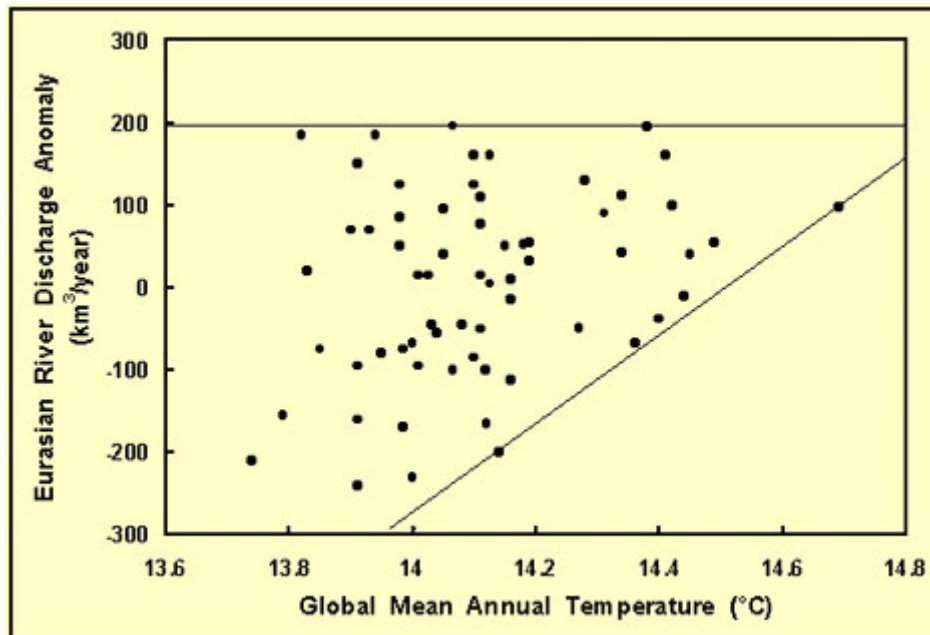
Last of all, worried about the possibility that enhanced freshwater delivery to the Arctic ocean by increased river flow could shut down the ocean's thermohaline circulation, Peterson *et al.* (2002) plotted annual values of the combined discharge of the six largest Eurasian Arctic rivers (Yenisey, Lena, Ob', Pechora, Kolyma and Severnaya Dvina) - which drain about two-thirds of the Eurasian Arctic landmass - against the globe's mean annual surface air temperature (SAT), after which they ran a simple linear regression through the data and determined that the combined discharge of the six rivers seems to rise by about 212 km<sup>3</sup>/year in response to a 1°C increase in mean global air temperature. Then, they calculated that for the high-end global warming predicted by the Intergovernmental Panel on Climate Change (IPCC) to occur by AD 2100, i.e., a temperature increase of 5.8°C, the warming-induced increase in freshwater discharge from the six rivers could rise by as much as 1260 km<sup>3</sup>/year (we calculate 5.8°C x 212 km<sup>3</sup>/year/°C = 1230 km<sup>3</sup>/year), which represents a 70% increase over the mean discharge rate of the last several years.

The link between this conclusion and the postulated shutting down of the thermohaline circulation of the world's oceans resides in the *hypothesis* that the delivery of such a large

addition of freshwater to the North Atlantic Ocean may slow - or even *stop* - that location's production of new deep water, which constitutes one of the driving forces of the great oceanic "conveyor belt." Although still discussed, this scenario is currently not as highly regarded as it was when Peterson *et al.* conducted their research, for a number of reasons, one that we have highlighted being the difficulty of accepting the tremendous extrapolation Peterson *et al.* make in extending their Arctic freshwater discharge vs. SAT relationship to the great length that is implied by the IPCC's predicted high-end warming of 5.8°C over the remainder of the current century.

Consider, for example, that "over the period of the discharge record, global SAT increased by [only] 0.4°C," according to Peterson *et al.* Do you think it reasonable to extend the relationship they derived across that small temperature range fully *fourteen and a half times further*? We surely don't, nor should any other rational person.

Consider also the Eurasian river discharge anomaly vs. global SAT plot of Peterson *et al.* (their Figure 4), which we have replotted in the figure below. Enclosing their data with simple straight-line upper and lower bounds, it can be seen that *the upper bound of the data does not change over the entire range of global SAT variability*, suggesting the very real possibility that the upper bound corresponds to a maximum Eurasian river discharge rate that cannot be exceeded in the real world under its current geographic and climatic configuration. The lower bound, on the other hand, rises so rapidly with increasing global SAT that *the two bounds intersect less than two-tenths of a degree above the warmest of Peterson et al.'s 63 data points*, suggesting that 0.2°C beyond the temperature of their warmest data point may be all the further any relationship derived from their data may validly be extrapolated.



*Annual Eurasian Arctic river discharge anomaly vs. annual global surface air temperature (SAT) over the period 1936 to 1999. Adapted from Peterson et al. (2002).*

In considering these observations, plus the findings of the other papers reviewed in this section, real-world data do not support the hydrologic negativism climate alarmists associate with both real-world and simulated global warming in Eurasia.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/s/sfrteurasia.php>.

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#### 4.4.2. North America

Brown *et al.* (1999) studied siliciclastic sediment grain size, planktonic foraminiferal and pteropod relative frequencies, and the carbon and oxygen isotopic compositions of two species of planktonic foraminifera in cored sequences of hemipelagic muds deposited over the past 5300 years in the northern Gulf of Mexico for evidence of variations in Mississippi River outflow characteristics over this time period. The results of their research indicated the occurrence of large *megafloods* - which they describe as having been "almost certainly larger than historical floods in the Mississippi watershed" - at 4700, 3500, 3000, 2500, 2000, 1200 and 300 years before present. These fluvial events, in their estimation, were likely "episodes of multidecadal duration," spawned by an export of extremely moist gulf air to midcontinental North America that was driven by naturally-occurring same-time-scale oscillations in Gulf of Mexico ocean currents.

Think what would happen *if*, in the words of the three researchers, the United States began to experience a *multidecadal episode* of "historically unprecedented precipitation and flooding in the Mississippi watershed." Before it was even in full-swing, the IPCC-inspired media would probably have driven the U.S. Senate to unanimous ratification of a dozen Kyoto protocols. But would they have been right to do so? Such an occurrence of "historically unprecedented" extreme weather sure sounds like what the climate models are predicting to occur as a consequence of the ongoing rise in the air's CO<sub>2</sub> content; but it is clear that these particular extreme events were in no way related to variations in atmospheric CO<sub>2</sub> concentration, as they occurred over a period of near-constancy in this atmospheric property. And if it's happened before, it can happen again. How easy it would be, therefore, to make a monumental mistake in our stewardship of the planet! Brown *et al.*'s study thus reminds us that we must not to rush to judgment in matters of such great importance.

Hidalgo *et al.* (2000) used a form of principal components analysis to reconstruct a history of streamflow in the Upper Colorado River Basin from information obtained from tree-ring data, after which they compared their results with the streamflow reconstruction of Stockton and Jacoby (1976). In doing so, they found their results were similar to those of the earlier 1976 study, but that their newer reconstruction responded with better fidelity to periods of below-average streamflow or regional drought. Hence, it was easier for them to see there had been "a near-centennial return period of extreme drought events in this region," going all the way back to the early 1500s, providing another demonstration of the cyclical nature of climate.

Also of great importance, Hidalgo *et al.*'s work provided additional evidence for the existence of past droughts that surpassed the worst of the 20th century. Consequently, it would not be surprising to see such a drought occur again; and if it lasted as long as such droughts have lasted in the past, it would likely be claimed by climate alarmists to have been caused by CO<sub>2</sub>-induced global warming. However, such need not be the case, since the most severe droughts of the past 500 years occurred at times when the air temperature and atmospheric CO<sub>2</sub> concentration were *much* lower than they are today; and, hence, they could just as easily occur now without any help from rising air temperatures and CO<sub>2</sub> concentrations as they did then.

Working in the same general area a few years later, Woodhouse *et al.* (2006) generated updated proxy reconstructions of water-year streamflow for four key streamflow gauges in the Upper Colorado River Basin (Green River at Green River, Utah; Colorado near Cisco, Utah; San Juan near Bluff, Utah; and Colorado at Lees Ferry, Arizona), "using an expanded tree-ring network and longer calibration records than in previous efforts." By these means they determined that the major drought of 2000-2004, "as measured by 5-year running means of water-year total flow at Lees Ferry ... is not without precedence in the tree ring record," and that "average reconstructed annual flow for the period 1844-1848 was lower." They also report that "two additional periods, in the early 1500s and early 1600s, have a 25% or greater chance of being as dry as 1999-2004," and that six other periods "have a 10% or greater chance of being drier." In addition, their work revealed that "longer duration droughts have occurred in the past," and that "the Lees Ferry reconstruction contains one sequence each of six, eight, and eleven consecutive years with flows below the 1906-1995 average."

"Overall," in the words of the three researchers, "these analyses demonstrate that severe, sustained droughts are a defining feature of Upper Colorado River hydroclimate." In fact, they conclude that "droughts more severe than any 20th to 21st century event occurred in the past," meaning the preceding few centuries. Interestingly, this finding is just the *opposite* of what climate alarmists would have one believe, i.e., that global warming brings with it more frequent and longer-lasting droughts of much greater severity. In stark contrast to this climate-model-based claim, the real-world record of the USA's Upper Colorado River Basin suggests that such droughts were more strongly associated with the much colder temperatures of the Little Ice Age.

Expanding the scope of investigation just a bit, and noting that "paleoclimatic studies indicate that the natural variability in 20th century [streamflow] gage records is likely only a subset of the full range of natural variability," while citing in support of this statement the studies of Stockton and Jacoby (1976), Smith and Stockton (1981), Meko *et al.* (2001) and Woodhouse (2001), Woodhouse and Lukas (2006) developed "a network of 14 annual streamflow reconstructions, 300-600 years long, for gages in the Upper Colorado and South Platte River basins in Colorado generated from new and existing tree-ring chronologies." The results indicated, as they describe it, that "the 20th century gage record does not fully represent the range of streamflow characteristics seen in the prior two to five centuries." Of greatest significance, in this regard, was probably the fact that "multi-year drought events more severe than the 1950s drought have occurred," and that "the greatest frequency of extreme low flow

events occurred in the 19th century," with a "clustering of extreme event years in the 1840s and 1850s."

These findings are of great importance to water resource planners. In addition, they provide a huge "security net" for climate-alarmists who predict the occurrence of both extreme droughts *and* floods in response to anthropogenic-produced increases in air temperature. This "assurance of fulfillment" of their prophetic pronouncements arises from the fact that historic streamflow variability is "only a subset of the full range of natural variability." This being the case, it can be appreciated that predictions of abnormal perturbations (relative to the past hundred or so years) of both wet and dry conditions likely *will* see fulfillment sometime in the future ... *but it need not be due to CO<sub>2</sub>-induced global warming*, for atmospheric CO<sub>2</sub> concentration and air temperature were both significantly lower than they are now - and will be throughout the 21st century - during the prior centuries of the Little Ice Age, when the greater *natural* variability in streamflow detected by Woodhouse and others occurred.

Working in an adjacent region of the western United States, Carson and Munroe (2005) used tree-ring data collected by Stockton and Jacoby (1976) from the Uinta Mountains of Utah to reconstruct mean annual discharge in the Ashley Creek watershed for the period 1637 to 1970. As a result of their efforts, significant persistent departures from the long-term mean were noted throughout the 334-year record of reconstructed streamflow. The periods 1637-1691 and 1741-1897 experienced reduced numbers of extremely large flows and increased numbers of extremely small flows, indicative of persistent drought or near-drought conditions. In contrast, there was an overall abundance of extremely large flows and relatively few extremely small flows during the periods 1692-1740 and 1898-1945, indicative of wetter conditions. These results provide yet another indication of the cyclical nature of climate. In addition, they provide still more evidence for the existence of past periods of extreme wetness and dryness with accompanying floods and droughts, when both air temperatures and atmospheric CO<sub>2</sub> concentrations were much lower than they were throughout the bulk of the 20th century.

Lins and Slack (1999) analyzed secular trends in streamflow for 395 climate-sensitive stream gage stations (including data from more than 1500 individual gages) located throughout the conterminous United States, some of which stations possessed data sets stretching all the way back to 1914. In doing so, they found many more up-trends than down-trends in streamflow nationally, with slight decreases "only in parts of the Pacific Northwest and the Southeast." These and other of their findings, as they describe them, indicate "the conterminous U.S. is getting wetter, *but less extreme* [our italics]," and it is difficult to conceive of a better result. As the world has warmed over the past century, the United States has gotten wetter in the mean, but less variable at the extremes, where floods and droughts occur.

Also studying the conterminous United States were McCabe and Wolock (2002), who for the period 1895-1999 evaluated (1) precipitation minus annual potential evapotranspiration, (2) the surplus water that eventually becomes streamflow, and (3) the water deficit that must be supplied by irrigation to grow vegetation at an optimum rate. This exercise revealed there was a statistically significant *increase* in the first two of these parameters, while for the third there

was *no change*, indicative of the fact that over the period of time climate alarmists describe as having witnessed a global warming that was *unprecedented* over the past one to two *millennia* (which they claim is leading to catastrophic moisture-related consequences for agriculture), water has actually become *more* available within the conterminous United States, and there has been *no increase* in the amount of water required for optimum plant growth.

Knox (2001) studied how conversion of the U.S. Upper Mississippi River Valley from prairie and forest to crop and pasture land by settlers in the early 1800s influenced subsequent watershed runoff and soil erosion rates. Initially, the conversion of the region's natural landscape to primarily agricultural use boosted surface erosion rates to values three to eight times greater than those characteristic of pre-settlement times. In addition, the land-use conversion increased peak discharges from high-frequency floods by 200 to 400%. Since the late 1930s, however, surface runoff has been decreasing; but the decrease "is not associated with climatic causes," according to Knox, who reports that "an analysis of temporal variation in storm magnitudes for the same period showed no statistically significant trend."

Other notable findings of Knox's study include the observation that since the 1940s and early 1950s, the magnitudes of the largest daily flows have been decreasing at the same time that the magnitude of the average daily baseflow has been increasing, indicating a trend toward fewer flood *and* drought conditions. Once again, therefore, we have a situation where global warming has coincided with a streamflow trend that is leading to the best of all possible worlds, i.e., one of greater water availability, but with fewer and smaller floods and droughts.

Molnar and Ramirez (2001) conducted a detailed watershed-based analysis of precipitation and streamflow trends for the period 1948-97 in a semiarid region of the southwestern United States, the Rio Puerco Basin of New Mexico. "At the annual timescale," as they describe it, "a statistically significant increasing trend in precipitation in the basin was detected." This trend was driven primarily by an increase in the number of rainy days in the moderate rainfall intensity range, with essentially no change at the high-intensity end of the spectrum. In the case of streamflow, however, there was no trend at the annual timescale; but monthly totals *increased* in *low-flow* months and *decreased* in *high-flow* months.

What are the implications of these findings? Increasing precipitation in a semiarid region sounds like a plus to us. Having most of the increase in the moderate rainfall intensity range also sounds like a plus. Increasing streamflow in normally low-flow months sounds good as well, as does decreasing streamflow in high-flow months. In fact, what more could one possibly want in terms of changes in precipitation and streamflow? ... especially in a world that according to the anti-CO<sub>2</sub> forces of the planet is supposed to be experiencing more extreme weather events and increases in floods and droughts? We once thought that by predicting both more floods and more droughts at one and the same time in response to global warming, climate alarmists were making sure they could not be proven wrong in their predictions of CO<sub>2</sub>-induced water-related calamities. In reviewing what nature reveals about the matter, however, it seems we erred in this assumption; they can be wrong on both counts, and they oftentimes are.



Shifting to a study of *snowmelt runoff* (SMR), McCabe and Clark (2005) note that most prior studies of this phenomenon in the western United States have depended on *trend analyses* to identify changes in timing, but they indicate that "trend analyses are unable to determine if a trend is gradual or a step change." This fact is crucial, they say, because when "changes in SMR timing have been identified by linear trends, there is a tendency to attribute these changes to global warming because of large correlations between linear trends in SMR timing and the increasing trend in global temperature." Therefore, using daily streamflow data for 84 stations in the western U.S., each with complete water-year information for the period 1950-2003, they conducted a number of analyses that enabled them to determine each station's mean streamflow trend over the last half century, as well as any *stepwise changes* that may have occurred in each data series.

As others before them had previously learned, the two researchers found that "the timing of SMR for many rivers in the western United States has shifted to earlier in the snowmelt season." However, they discovered that "the shift to earlier SMR has not been a gradual trend, but appears to have occurred as a step change during the mid-1980s," which shift was "related to a regional step increase in April-July temperatures during the mid-1980s." As a result, and after discussing various other possible reasons for what they had discovered, McCabe and Clark concluded that "the observed change in the timing of SMR in the western United States is a regional response to natural climatic variability and may not be related to global trends in temperature."

Over in Minnesota, Novotny and Stefan (2006) analyzed streamflow records (extending up to the year 2002, with lengths ranging from 53 to 101 years) obtained from 36 gauging stations in five major river basins of the state, deriving histories of seven annual streamflow statistics: "mean annual flow, 7-day low flow in winter, 7-day low flow in summer, peak flow due to snow melt runoff, peak flow due to rainfall, as well as high and extreme flow days (number of days with flow rates greater than the mean plus one or two standard deviations, respectively)." In doing so, they found significant trends in each of the seven streamflow statistics throughout the state, but that in most cases "the trends are not monotonic but periodic," and they determined, as might have been expected, that "the mean annual stream flow changes are well correlated with total annual precipitation changes."

Most significantly, they found that *peak flood flows due to snowmelt runoff* "are not changing at a significant rate throughout the state," but that 7-day low flows or *base flows* are "increasing in the Red River of the North, Minnesota River and Mississippi River basins during both the summer and winter," that the "low flows are changing at a significant rate in a significant number of stations and at the highest rates in the past 20 years," and that "this finding matches results of other studies which found low flows increasing in the upper Midwest region including Minnesota (Lins and Slack, 1999; Douglas *et al.*, 2000)."

With respect to the ramifications of their findings, the two researchers write than "an increase in mean annual streamflow in Minnesota would be welcome," as "it could provide more aquatic habitat, better water quality, and more recreational opportunities, among other benefits."

Likewise, they say that "water quality and aquatic ecosystems should benefit from increases in low flows in both the summer and winter, since water quality stresses are usually largest during low flow periods." In addition, they say "other good news is that spring floods (from snowmelt), the largest floods in Minnesota, have not been increasing significantly." Clearly, therefore, even in the fabled "Land of Ten Thousand Lakes," increasing base flows of rivers and streams are tending to *enhance* the environment, in response to - or in spite of (take your pick) - the supposedly unprecedented increases in air temperature and atmospheric CO<sub>2</sub> concentration that have been experienced concurrently.

In a study that covered parts of two countries, Rood *et al.* (2005) performed an empirical analysis of streamflow trends for rivers fed by relatively pristine watersheds in the central Rocky Mountain Region of North America that extends from Wyoming in the United States through British Columbia in Canada. In doing so, they applied both parametric and non-parametric statistical analyses to assess nearly a century of annual discharge (ending about 2002) along 31 river reaches that drain this part of North America. These analyses revealed that river flows in this region *declined* over the past century by an average of 0.22% per year, with four of them exhibiting recent decline rates exceeding 0.5% per year. This finding, in the words of Rood *et al.*, "contrasts with the many current climate change predictions that [this specific] region will become warmer and wetter in the near-future." Once again, therefore, the models appear to have gotten it all wrong for a large portion of North America.

Working entirely in Canada, where about three quarters of the country is drained by rivers that discharge their water into the Arctic and North Atlantic Oceans, Déry and Wood (2005) analyzed hydrometric data from 64 northern Canadian rivers that drain more than half of the country's landmass for the period 1964-2003. Then, after assessing both variability and trends, they explored the influence of large-scale teleconnections as possible drivers of the trends they detected. This work indicated there was a statistically significant mean decline of approximately 10% in the discharge rates of the 64 rivers over the four decades of their study, which was nearly identical to the decline in precipitation falling over northern Canada between 1964 and 2000. These facts led the two scientists to conclude that the changes in river discharge they observed were driven "primarily by precipitation rather than evapotranspiration." As for the *cause* of the precipitation/river discharge decline, statistically significant links were found between the decline and the Arctic Oscillation, the El Niño/Southern Oscillation and the Pacific Decadal Oscillation. Consequently, the results of this study indicate there is nothing unusual about the four-decade-long trends in northern Canada river discharge rates, which means there is nothing in these trends that would suggest a global warming impact. If anything, the results argue *against* the worrisome climate-alarmist notion, for state-of-the-art climate models generally suggest that global warming will *enhance* river discharge rates due to an intensified hydrologic cycle. The trends observed here, however, are just the *opposite*; and it would appear they are the products of natural variations in natural phenomena.

Also in Canada Campbell (2002) analyzed the grain sizes of sediment cores obtained from Pine Lake, Alberta, to provide a non-vegetation-based high-resolution record of climate variability

for this part of North America over the past 4000 years. This research effort revealed the existence of periods of both increasing and decreasing grain size (a proxy for moisture availability) throughout the 4000-year record at decadal, centennial and millennial time scales. The most predominant departures included several-centuries-long epochs that corresponded to the Little Ice Age (about AD 1500-1900), the Medieval Warm Period (about AD 700-1300), the Dark Ages Cold Period (about BC 100 to AD 700) and the Roman Warm Period (about BC 900-100). In addition, a standardized median grain-size history revealed that the highest rates of stream discharge during the past 4000 years occurred during the Little Ice Age approximately 300-350 years ago. During this time, grain sizes were about 2.5 standard deviations above the 4000-year mean. In contrast, the lowest rates of streamflow were observed around AD 1100, when median grain sizes were nearly 2 standard deviations below the 4000-year mean, while most recently, grain size over the past 150 years has generally remained above average.

The Pine Lake sediment record convincingly demonstrates the reality of the non-CO<sub>2</sub>-induced millennial-scale climatic oscillation that has alternately brought several-century-long periods of dryness and wetness to the southern Alberta region of North America during concomitant periods of relative global warmth and coolness, respectively, revealing a relationship that was not evident in the prior streamflow studies reviewed here that did not stretch all the way back in time to the Medieval Warm Period. It also demonstrates there is nothing unusual about the region's current moisture status, which suggests that the planet may still have a bit of warming to do before the Current Warm Period is fully developed.

In a final study from Canada, St. George (2007) begins by noting that the study of Burn (1994) suggested that a doubling of the air's CO<sub>2</sub> content could increase the severity and frequency of droughts in the prairie provinces of Canada (Alberta, Saskatchewan, Manitoba), but that results from an ensemble of climate models suggest that runoff in the Winnipeg River region of southern Manitoba, as well as runoff in central and northern Manitoba, could increase 20-30% by the middle of the 21st century (Milly *et al.*, 2005). To help resolve this dichotomy, St. George obtained daily and monthly streamflow data from nine gauge stations within the Winnipeg River watershed from the Water Survey of Canada's HYDAT data archive, plus precipitation and temperature data from Environment Canada's Adjusted Historical Canadian Climate Data archive, and analyzed them for trends over the period 1924-2003.

This work revealed, in the words of St. George, that "mean annual flows have increased by 58% since 1924 ... with winter streamflow going up by 60-110%," primarily because of "increases in precipitation during summer and autumn." In addition, he notes that similar "changes in annual and winter streamflow are observed in records from both regulated and unregulated portions of the watershed, which point to an underlying cause related to climate." Countering these positive findings, however, St. George says there are "reports of declining flow for many rivers in the adjacent Canadian prairies," citing the studies of Westmacott and Burn (1997), Yulianti and Burn (1998), Dery and Wood (2005) and Rood *et al.* (2005). Consequently, just as there are conflicting predictions about the *future* water status of portions of the Prairie Provinces of Canada, especially in Manitoba, so too are there conflicting reports about *past* streamflow trends in this region. Hence, it's anybody's guess as to what will actually occur in the years and

decades ahead, although based on the observed trends he discovered, St. George believes "the potential threats to water supply faced by the Canadian Prairie Provinces over the next few decades will not include decreasing streamflow in the Winnipeg River basin."

In concluding this subsection, we report on the recent *global* study of Milliman *et al.* (2008), who computed temporal discharge trends for 137 rivers over the last half of the 20th century that provide what they call a "reasonable global representation," as their combined drainage basins represent about 55% of the land area draining into the global ocean. In the words of the five researchers, "between 1951 and 2000 cumulative discharge for the 137 rivers remained statistically unchanged." In addition, they report that "global on-land precipitation between 1951 and 2000 remained statistically unchanged." Then, in a simple and straightforward conclusion, Milliman *et al.* write that "neither discharge nor precipitation changed significantly over the last half of the 20th century, offering little support to a global intensification of the hydrological cycle," such as is generally claimed to be a consequence of CO<sub>2</sub>-induced global warming.

Thus, we note there appear to be few real-world data that provide any significant support for the contention that CO<sub>2</sub>-induced global warming will lead to more frequent and/or more severe increases and decreases in streamflow that result in, or are indicative of, more frequent and/or more severe floods and droughts. In fact, in the vast majority of cases, observed trends appear to be just the *opposite* of what is predicted to occur. Not only are real-world observations nearly all *not undesirable*, they are *positive*, and typically *extremely* so.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/s/sfrtnorthamerica.php>.

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#### **4.5. Greenland**

A long succession of climate models has consistently predicted that CO<sub>2</sub>-induced global warming should be significantly amplified in earth's polar regions and that the first signs of humanity's expected impact on the world's weather should thus be manifest there. In consequence of such warming, the models further predict the rapid disintegration of the Greenland Ice sheet and subsequent raising of global sea level on the order of 7 feet. But how valid are such claims? Is the so-called unprecedented warmth of the past two millennia exerting a notable influence on the Greenland ice sheet? We answer such questions in the subsections below, citing numerous scientific studies.

Additional information on this topic, including reviews on Greenland not discussed here, can be found at [http://www.co2science.org/subject/g/subject\\_g.php](http://www.co2science.org/subject/g/subject_g.php) under the heading Greenland.

##### **4.5.1. Temperature History**

Dahl-Jensen *et al.* (1998) used data from two ice sheet boreholes to reconstruct the temperature history of Greenland over the past 50,000 years. Their analysis indicated that temperatures on the Greenland Ice Sheet during the Last Glacial Maximum (about 25,000 years ago) were  $23 \pm 2$  °C colder than at present. After the termination of the glacial period, however, temperatures increased steadily to a value that was 2.5°C warmer than at present, during the Climatic Optimum of 4,000 to 7,000 years ago. The Medieval Warm Period and Little Ice Age were also evident in the borehole data, with temperatures 1°C warmer and 0.5-0.7°C

cooler than at present, respectively. Then, after the Little Ice Age, the group of seven scientists reports that "temperatures reached a maximum around 1930 AD" and that "temperatures have *decreased* [our italics] during the last decades."

The results of this study stand in stark contrast to the predictions of general circulation models of the atmosphere, which consistently suggest there should have been a significant CO<sub>2</sub>-induced warming in high northern latitudes over the past several decades. They also depict large temperature excursions over the last 10,000 years, when the air's CO<sub>2</sub> content was relatively stable. Each of these observations raises serious doubts about the models' ability to correctly forecast earth's climatic response to the ongoing rise in the air's CO<sub>2</sub> content.

In another study of Greenland climate that included both glacial and interglacial periods, Bard (2002) reviews the concept of *rapid climate change*. Of this phenomenon, he writes that "it is now recognized that the ocean-atmosphere system exhibits several stable regimes under equivalent external forcings," and that "the transition from one state to another occurs very rapidly when certain climatic parameters attain threshold values." Specifically, he notes that *in the models* "a slight increase in the freshwater flux above the modern level  $F$  produces a decrease in the NADW [North Atlantic Deep Water] convection and a moderate cooling in the North Atlantic," but that "the system flips to another state once the flux reaches a threshold value  $F + \Delta F$ ," which state has no deep convection and "is characterized by surface temperatures up to 6°C lower in and around the North Atlantic."

With respect to what has been learned from *observations*, Bard concentrates on the region of the North Atlantic, describing glacial-period millennial-scale episodes of dramatic warming called Dansgaard-Oeschger events (with temperature increases "of more than 10°C"), which are evident in Greenland ice core records, as well as episodes of "drastic cooling" called Heinrich events (with temperature drops "of up to about 5°C"), which are evident in sea surface temperature records derived from the study of North Atlantic deep-sea sediment cores.

In the Greenland record, according to Bard, the progression of these events is such that "the temperature warms abruptly to reach a maximum and then slowly decreases for a few centuries before reaching a threshold, after which it drops back to the cold values that prevailed before the warm event." He also reports that "models coupling the atmosphere, ocean, and ice sheets are still unable to correctly simulate that variability on all scales in both time and space," which suggests we do not fully understand the dynamics of these rapid climate changes. Indeed, Bard forcefully states that "all the studies so far carried out fail to answer the crucial question: How close are we to the next bifurcation [which could cause a rapid change-of-state in earth's climate system]?" In this regard, he notes that "an intense debate continues in the modeling community about the reality of such instabilities under *warm* conditions [our italics]," which is a particularly important point, seeing that all dramatic warming and cooling events that have been detected to date have occurred in either full glacials or transitional periods between glacials and interglacials.

This latter real-world *fact* clearly suggests we are unlikely to experience any dramatic warming or cooling surprises in the near future, *as long as the earth does not begin drifting towards glacial conditions*, which is but another reason to not be concerned about the ongoing rise in the air's CO<sub>2</sub> content. In fact, it suggests that allowing more CO<sub>2</sub> to accumulate in the atmosphere actually provides an effective "insurance policy" against abrupt climate change; for interglacial warmth seems to inoculate the planet against climatic instabilities, allowing only the mild millennial-scale climatic oscillation that alternately brings the earth slightly warmer and cooler conditions typical of the Medieval Warm Period and Little Ice Age. Hence, and in light of the fact that the four preceding interglacials basked in temperatures fully 2°C warmer than those of the current interglacial (Petit *et al.*, 1999) without suffering any adverse climatic consequences, humanity would be wise to not surrender the *true* environmental insurance policy we worked so hard to put in place by depositing the excess CO<sub>2</sub> we produced over the course of the Industrial Revolution into the atmosphere, where it clearly does both the climate and the biosphere great good.

Focusing on the more pertinent period of the current interglacial or Holocene, we next consider a number of papers that come to bear upon the reality of the Medieval Warm Period and Little Ice Age: two well-known multi-century periods of significant climatic aberration, whose existence the world's climate alarmists simply refuse to acknowledge. And why do they refuse to acknowledge them? Because these periods of modest climatic aberration, plus the analogous warm and cool periods that preceded them (the Roman Warm Period and Dark Ages Cold Period), provide strong evidence for the existence of a millennial-scale oscillation of climate that is unforced by changes in the air's CO<sub>2</sub> content, which in turn suggests that the global warming of the Little Ice Age-to-Modern Warm Period *transition* was likely *totally independent* of the coincidental concomitant increase in the air's CO<sub>2</sub> content that accompanied the Industrial Revolution.

We begin with the study of Keigwin and Boyle (2000), who briefly reviewed what is known about the millennial-scale oscillation of earth's climate that is evident in a wealth of proxy climate data from around the world. Stating that "mounting evidence indicates that the Little Ice Age was a global event, and that its onset was synchronous within a few years in both Greenland and Antarctica," they remark that *in Greenland* it was characterized by a cooling of approximately 1.7°C. Likewise, in an article entitled "Was the Medieval Warm Period Global?", Broecker (2001) answers yes, citing borehole temperature data that reveal the magnitude of the temperature drop over Greenland from the peak warmth of the Medieval Warm Period (800 to 1200 A.D.) to the coldest part of the Little Ice Age (1350 to 1860 A.D.) to have been approximately 2°C, and noting that as many as *six thousand* borehole records from *all continents of the world* confirm that the earth was a significantly warmer place a thousand years ago than it is today.

McDermott *et al.* (2001) derived a  $\delta^{18}\text{O}$  record from a stalagmite discovered in Crag Cave in southwestern Ireland, after which they compared this record with the  $\delta^{18}\text{O}$  records from the GRIP and GISP2 ice cores from Greenland. In doing so, they found evidence for "centennial-scale  $\delta^{18}\text{O}$  variations that correlate with subtle  $\delta^{18}\text{O}$  changes in the Greenland ice cores,



indicating regionally coherent variability in the early Holocene." They additionally report that the Crag Cave data "exhibit variations that are broadly consistent with a Medieval Warm Period at  $\sim 1000 \pm 200$  years ago and a two-stage Little Ice Age, as reconstructed by inverse modeling of temperature profiles in the Greenland Ice Sheet." Also evident in the Crag Cave data were the  $\delta^{18}\text{O}$  signatures of the earlier Roman Warm Period and Dark Ages Cold Period that comprised the prior such cycle of climate in that region; and in concluding they reiterate the important fact that the coherent  $\delta^{18}\text{O}$  variations in the records from both sides of the North Atlantic "indicate that many of the subtle multicentury  $\delta^{18}\text{O}$  variations in the Greenland ice cores reflect regional North Atlantic margin climate signals rather than local effects."

Another study that looked at temperature variations on both sides of the North Atlantic was that of Seppa and Birks (2002), who used a recently developed pollen-climate reconstruction model and a new pollen stratigraphy from Toskaljavri, a tree-line lake in the continental sector of northern Fenoscandia (located just above  $69^\circ\text{N}$  latitude), to derive quantitative estimates of annual precipitation and July mean temperature. The two scientists say their reconstructions "agree with the traditional concept of a 'Medieval Warm Period' (MWP) and 'Little Ice Age' in the North Atlantic region (Dansgaard *et al.*, 1975)." Specifically, they report there is "a clear correlation between our MWP reconstruction and several records from Greenland ice cores," and that "comparisons of a smoothed July temperature record from Toskaljavri with measured borehole temperatures of the GRIP and Dye 3 ice cores (Dahl-Jensen *et al.*, 1998) and the  $\delta^{18}\text{O}$  record from the Crete ice core (Dansgaard *et al.*, 1975) show the strong similarity in timing of the MWP between the records." Last of all, they note that "July temperature values during the Medieval Warm Period (ca. 1400-1000 cal yr B.P.) were ca.  $0.8^\circ\text{C}$  higher than at present," where *present* means the last six decades of the 20th century.

Concentrating solely on Greenland and its immediate environs are several other papers, among which is the study of Wagner and Melles (2001), who retrieved a sediment core from a lake on an island situated just off Liverpool Land on the east coast of Greenland. Analyzing it for a number of properties related to the past presence of seabirds there, they obtained a 10,000-year record that tells us much about the region's climatic history.

Key to the study were certain biogeochemical data that reflected variations in seabird breeding colonies in the catchment area of the lake. These data revealed high levels of the various parameters measured by Wagner and Melles between about 1100 and 700 years before present (BP) that were indicative of the summer presence of significant numbers of seabirds during that "medieval warm period," as they describe it, which had been preceded by a several-hundred-year period of little to no inferred bird presence. Then, after the Medieval Warm Period, the data suggested another absence of birds during what they refer to as "a subsequent Little Ice Age," which they note was "the coldest period since the early Holocene in East Greenland." Their data also showed signs of a "resettlement of seabirds during the last 100 years, indicated by an increase of organic matter in the lake sediment and confirmed by bird observations." However, values of the most recent data were not as great as those obtained from the earlier Medieval Warm Period; and temperatures derived from two Greenland ice

cores led to the same conclusion: it was warmer at various times between 1100 to 700 years BP than it was over the 20th century.

Kaplan *et al.* (2002) also worked with data obtained from a small lake, this one in southern Greenland, analyzing sediment physical-chemical properties, including magnetic susceptibility, density, water content, and biogenic silica and organic matter concentrations. They discovered that "the interval from 6000 to 3000 cal yr BP was marked by warmth and stability." Thereafter, however, the climate cooled "until its culmination during the Little Ice Age," but from 1300-900 years BP, there was a partial amelioration of climate (the Medieval Warm Period) that was associated with an approximate 1.5°C rise in temperature.

Following another brief warming between AD 1500 and 1750, the second and more severe portion of the Little Ice Age occurred, which was in turn followed by "naturally initiated post-Little Ice Age warming since AD 1850, which is recorded throughout the Arctic." Last of all, they report that Viking "colonization around the northwestern North Atlantic occurred during peak Medieval Warm Period conditions that ended in southern Greenland by AD 1100," noting that Norse movements around the region thereafter "occurred at perhaps the worst time in the last 10,000 years, in terms of the overall stability of the environment for sustained plant and animal husbandry."

We can further explore these aspects of Greenland's climatic history from three important papers that reconstructed environmental conditions in the vicinity of Igaliku Fjord, South Greenland, before, during and after the period of Norse habitation of this and other parts of the ice-covered island's coast, beginning with the study of Lassen *et al.* (2004), who provide some historical background to their palaeoclimatic work by reporting that "the Norse, under Eric the Red, were able to colonize South Greenland at AD 985, according to the Icelandic Sagas, owing to the mild Medieval Warm Period climate with favorable open-ocean conditions." They also mention, in this regard, that the arrival of the gritty Norsemen was "close to the peak of Medieval warming recorded in the GISP2 ice core which was dated at AD 975 (Stuiver *et al.*, 1995)," while we additionally note that Esper *et al.* (2002) independently identified the peak warmth of this period throughout North American extratropical latitudes as "occurring around 990." Hence, it would appear that the *window of climatic opportunity* provided by the peak warmth of the Medieval Warm Period was indeed a major factor enabling seafaring Scandinavians to establish long-enduring settlements on the coast of Greenland.

As time progressed, however, the glowing promise of the *apex* of Medieval *warmth* gave way to the debilitating reality of the *depth* of Little Ice Age *cold*. Jensen *et al.* (2004), for example, report that the diatom record of Igaliku Fjord "yields evidence of a relatively moist and warm climate at the beginning of settlement, which was crucial for Norse land use," but that "a regime of more extreme climatic fluctuations began soon after AD 1000, and after AD c. 1350 cooling became more severe." Lassen *et al.* additionally note that "historical documents on Iceland report the presence of the Norse in South Greenland for the last time in AD 1408," during what they describe as a period of "unprecedented influx of (ice-loaded) East Greenland Current water masses into the innermost parts of Igaliku Fjord." They also report that "studies

of a Canadian high-Arctic ice core and nearby geothermal data (Koerner and Fisher, 1990) correspondingly show a significant temperature lowering at AD 1350-1400," when, in their words, "the Norse society in Greenland was declining and reaching its final stage probably before the end of the fifteenth century." Consequently, what the relative warmth of the Medieval Warm Period provided the Norse settlers, the relative cold of the Little Ice Age took from them: the ability to survive on Greenland.

Many more details of this incredible saga of five centuries of Nordic survival at the foot of the Greenland Ice Cap are provided by the trio of papers addressing the palaeohistory of Igaliku Fjord. Based on a high-resolution record of the fjord's subsurface water-mass properties derived from analyses of benthic foraminifera, Lassen *et al.* conclude that stratification of the water column, with Atlantic water masses in its lower reaches, appears to have prevailed throughout the last 3200 years, *except for the Medieval Warm Period*. During this period, which they describe as occurring between AD 885 and 1235, the outer part of Igaliku Fjord experienced enhanced vertical mixing (which they attribute to increased wind stress) that would have been expected to increase nutrient availability there. A similar conclusion was reached by Roncaglia and Kuijpers (2004), who found evidence of increased bottom-water ventilation between AD 960 and 1285. Hence, based on these findings, plus evidence of the presence of *Melonis barleeanus* during the Medieval Warm Period (the distribution of which is mainly controlled by the presence of partly decomposed organic matter), Lassen *et al.* conclude that surface productivity in the fjord during this interval of unusual relative warmth was "high and thus could have provided a good supply of marine food for the Norse people."

Shortly thereafter, the cooling that led to the Little Ice Age was accompanied by a gradual re-stratification of the water column, which curtailed nutrient upwelling and reduced the high level of marine productivity that had prevailed throughout the Medieval Warm Period. These linked events, according to Lassen *et al.*, "contributed to the loss of the Norse settlement in Greenland." Indeed, with deteriorating growing conditions on land and simultaneous reductions in oceanic productivity, the odds were truly stacked against the Nordic colonies, and it was only a matter of time before their fate was sealed. As Lassen *et al.* describe it, "around AD 1450, the climate further deteriorated with further increasing stratification of the water-column associated with stronger advection of (ice-loaded) East Greenland Current water masses." This development, in their words, led to an even greater "increase of the ice season and a decrease of primary production and marine food supply," which "could also have had a dramatic influence on the local seal population and thus the feeding basis for the Norse population."

The end result of these several conjoined phenomena, in the words of Lassen *et al.*, was that "climatic and hydrographic changes in the area of the Eastern Settlement were significant in the crucial period when the Norse disappeared." Also, Jensen *et al.* report that "geomorphological studies in Northeast Greenland have shown evidence of increased winter wind speed, particularly in the period between AD 1420 and 1580 (Christiansen, 1998)," noting that "this climatic deterioration coincides with reports of increased sea-ice conditions that caused difficulties in using the old sailing routes from Iceland westbound and further southward along

the east coast of Greenland, forcing sailing on more southerly routes when going to Greenland (Seaver, 1996)."

In light of these observations, Jensen *et al.* state that "life conditions certainly became harsher during the 500 years of Norse colonization," and that this severe cooling-induced environmental deterioration "may very likely have hastened the disappearance of the culture." At the same time, it is also clear that the more favorable living conditions associated with the *peak warmth* of the Medieval Warm Period -- which occurred between approximately AD 975 (Stuiver *et al.*, 1995) and AD 990 (Esper *et al.*, 2002) -- were what originally enabled the Norse to successfully colonize the region. Furthermore, in the thousand-plus subsequent years, there has *never* been a sustained period of comparable warmth, nor of comparable terrestrial or marine productivity, either locally or hemispherically (and likely globally, as well), the strident protestations of Mann *et al.* (2003) notwithstanding. Hence, since the peak warmth of the Medieval Warm Period was caused by something quite apart from elevated levels of atmospheric CO<sub>2</sub>, or any other greenhouse gas, for that matter, there is no reason to not believe that a return engagement of that same factor or group of factors is responsible for the even *lesser* warmth of today.

Concentrating finally on the 20th century, Hanna and Cappelen (2003) determined the air temperature history of coastal southern Greenland from 1958-2001, based on data from eight Danish Meteorological Institute stations in coastal and near-coastal southern Greenland, as well as the concomitant sea surface temperature (SST) history of the Labrador Sea off southwest Greenland, based on three previously published and subsequently extended SST data sets (Parker *et al.*, 1995; Rayner *et al.*, 1996; Kalnay *et al.*, 1996). The coastal temperature data showed a *cooling* of 1.29°C over the period of study, while two of the three SST databases also depicted cooling: by 0.44°C in one case and by 0.80°C in the other. Both the land-based air temperature and SST series followed similar patterns and were strongly correlated, but with no obvious lead/lag either way. In addition, it was determined that the cooling was "significantly inversely correlated with an increased phase of the North Atlantic Oscillation (NAO) over the past few decades." The two researchers say that this "NAO-temperature link doesn't explain what caused the observed cooling in coastal southern Greenland but it does lend it credibility."

In referring to what they call "this important regional exception to recent 'global warming'," Hanna and Cappelen note that the "recent cooling may have significantly added to the mass balance of at least the southern half of the [Greenland] Ice Sheet." Consequently, since this part of the ice sheet is the portion that would likely be the first to experience melting in a warming world, it would appear that whatever caused the cooling has not only *protected* the Greenland Ice Sheet against warming-induced disintegration but actually *fortified* it against that possibility.

Several other studies have also reported late-20th-century cooling on Greenland. Based on mean monthly temperatures of 37 Arctic and 7 sub-Arctic stations, as well as temperature anomalies of 30 grid-boxes from the updated data set of Jones, for example, Przybylak (2001) found that "the level of temperature in Greenland in the last 10-20 years is similar to that

observed in the 19th century." Likewise, in a study that utilized satellite imagery of the Odden ice tongue (a winter ice cover that occurs in the Greenland Sea with a length of about 1300 km and an aerial coverage of as much as 330,000 square kilometers) plus surface air temperature data from adjacent Jan Mayen Island, Comiso *et al.* (2001) determined that the ice phenomenon was "a relatively smaller feature several decades ago," due to the warmer temperatures that were prevalent at that time. In addition, they report that observational evidence from Jan Mayen Island indicates that temperatures there actually cooled at a rate of  $0.15 \pm 0.03^\circ\text{C}$  per decade during the past 75 years.

Concluding our discussion of this final aspect of Greenland's temperature history, we note that in a study of three coastal stations in southern and central Greenland that possess almost uninterrupted temperature records between 1950 and 2000, Chylek *et al.* (2004) discovered that "summer temperatures, which are most relevant to Greenland ice sheet melting rates, do not show any persistent increase during the last fifty years." In fact, working with the two stations with the longest records (both over a century in length), they determined that coastal Greenland's peak temperatures occurred between 1930 and 1940, and that the subsequent decrease in temperature was so substantial and sustained that current coastal temperatures "are about  $1^\circ\text{C}$  below their 1940 values." Furthermore, they note that "at the summit of the Greenland ice sheet the summer average temperature has decreased at the rate of  $2.2^\circ\text{C}$  per decade since the beginning of the measurements in 1987." Hence, as with the Arctic as a whole, it would appear that Greenland has not experienced any net warming over the most dramatic period of atmospheric  $\text{CO}_2$  increase on record. In fact, it has *cooled* during this period ... and cooled *significantly*.

At the *start* of the 20th century, however, Greenland was warming, as it emerged, along with the rest of the world, from the depths of the Little Ice Age. What is more, between 1920 and 1930, when the atmosphere's  $\text{CO}_2$  concentration rose by a mere 3 to 4 ppm, there was a *phenomenal* warming at all five coastal locations for which contemporary temperature records are available. In fact, in the words of Chylek *et al.*, "average annual temperature rose between  $2$  and  $4^\circ\text{C}$  [and by as much as  $6^\circ\text{C}$  in the winter] in less than ten years." And this warming, as they note, "is also seen in the  $^{18}\text{O}/^{16}\text{O}$  record of the Summit ice core (Steig *et al.*, 1994; Stuiver *et al.*, 1995; White *et al.*, 1997)."

In commenting on this dramatic temperature rise, which they call the *great Greenland warming of the 1920s*, Chylek *et al.* conclude that "since there was no significant increase in the atmospheric greenhouse gas concentration during that time, the Greenland warming of the 1920s demonstrates that a large and rapid temperature increase can occur over Greenland, and perhaps in other regions of the Arctic, due to internal climate variability such as the NAM/NAO [Northern Annular Mode/North Atlantic Oscillation], without a significant anthropogenic influence." These facts thus led them to speculate that "the NAO may play a crucial role in determining local Greenland climate during the 21st century, resulting in a local climate that may defy the global climate change."

In further contemplating the results of the study of Chylek *et al.*, it is clear that the entire history of anthropogenic CO<sub>2</sub> emissions since the inception of the Industrial Revolution has had *no discernable impact* on Greenland air temperatures. Hence, it can readily be appreciated that there is absolutely no substance to the claim that Greenland provides evidence for an impending CO<sub>2</sub>-induced warming of *any* magnitude. What these many studies of the temperature history of Greenland do depict is long-term oscillatory cooling ever since the Climatic Optimum of the mid-Holocene, when it was perhaps 2.5°C warmer than it is now, within which cooling trend is included the Medieval Warm Period, when it was about 1°C warmer than it is currently, and the Little Ice Age, when it was 0.5 to 0.7°C cooler than now, after which temperatures rebounded to a new maximum in the 1930s, only to fall steadily thereafter.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/g/greenland.php>.

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#### 4.5.2. Contribution to Sea Level

Studies of the growth and decay of polar ice sheets are of great importance because of the relationships of these phenomena to global warming and the impacts they can have on sea level. In this section, therefore, we review a number of such studies that pertain to the Greenland Ice Sheet.

In the 24 March 2006 issue of *Science*, a number of commentaries heralded accelerating discharges of glacial ice from Greenland and Antarctica, while dispensing dire warnings of an imminent large, rapid and accelerating sea-level rise (Bindshadler, 2006; Joughin, 2006; Kerr, 2006; Kennedy and Hanson, 2006). This distressing news was based largely on three reports published in the same issue (Ekstrom *et al.*, 2006; Otto-Bliesner *et al.*, 2006; Overpeck *et al.*, 2006), wherein the unnerving phenomena were attributed to anthropogenic-induced global warming, which is widely claimed to be due primarily to increases in the air's  $\text{CO}_2$  content that are believed to be driven by the burning of ever increasing quantities of fossil fuels such as coal, gas and oil. But does all of this make any sense?



Consider the report of Ekstrom *et al.*, who studied "glacial earthquakes" caused by sudden sliding motions of glaciers on Greenland. Over the period Jan 1993 to Oct 2005, they determined that (1) *all* of the best-recorded quakes were associated with major outlet glaciers on the east and west coasts of Greenland between approximately 65 and 76°N latitude, (2) "a clear increase in the number of events is seen starting in 2002," and (3) "to date in 2005, twice as many events have been detected as in any year before 2002."

With respect to the *reason* for the recent increase in glacial activity on Greenland, Clayton Sandell of ABC News (23 March 2006) quoted Ekstrom as saying "I think it is very hard not to associate this with global warming," which sentiment appears to be shared by almost all of the authors of the seven *Science* articles. Unwilling to join in that conclusion, however, was Joughin, who in the very same issue presented histories of summer temperature at four coastal Greenland stations located within the same latitude range as the sites of the glacial earthquakes, which histories suggest that it was warmer in this region back in the 1930s than it was over the period of Ekstrom *et al.*'s analysis.

Based on these data, Joughin concluded that the recent warming in Greenland "is too short to determine whether it is an anthropogenic effect or natural variability," a position that is supported - and in some cases even more rigorously - by numerous scientists who have researched the issue, as noted in the following brief synopses of some of their studies.

Hanna and Cappelen (2003) determined the air temperature history of coastal southern Greenland from 1958-2001, based on data from eight Danish Meteorological Institute stations in coastal and near-coastal southern Greenland, as well as the concomitant sea surface temperature (SST) history of the Labrador Sea off southwest Greenland, based on three previously published and subsequently extended SST data sets (Parker *et al.*, 1995; Rayner *et al.*, 1996; Kalnay *et al.*, 1996). Their analyses revealed that the coastal temperature data showed a cooling of 1.29°C over the period of study, while two of the three SST databases also depicted cooling: by 0.44°C in one case and by 0.80°C in the other. In addition, it was determined that the cooling was "significantly inversely correlated with an increased phase of the North Atlantic Oscillation over the past few decades."

In an even broader study based on mean monthly temperatures of 37 Arctic and 7 sub-Arctic stations, as well as temperature anomalies of 30 grid-boxes from the updated data set of Jones, Przybylak (2000) found that (1) "in the Arctic, the highest temperatures since the beginning of instrumental observation occurred clearly in the 1930s," (2) "even in the 1950s the temperature was higher than in the last 10 years," (3) "since the mid-1970s, the annual temperature shows no clear trend," and (4) "the level of temperature in Greenland in the last 10-20 years is similar to that observed in the 19th century." These findings led him to conclude that the meteorological record "shows that the observed variations in air temperature in the real Arctic are in many aspects not consistent with the projected climatic changes computed by climatic models for the enhanced greenhouse effect," because, in his words, "the temperature predictions produced by numerical climate models significantly differ from those actually observed."

In a study that utilized satellite imagery of the Odden ice tongue (a winter ice cover that occurs in the Greenland Sea with a length of about 1300 km and an aerial coverage of as much as 330,000 square kilometers) plus surface air temperature data from adjacent Jan Mayen Island, Comiso *et al.* (2001) determined that the ice phenomenon was "a relatively smaller feature several decades ago," due to the warmer temperatures that were prevalent at that time. In fact, they report that observational evidence from Jan Mayen Island indicates that temperatures there actually cooled at a rate of  $0.15 \pm 0.03^{\circ}\text{C}$  per decade throughout the prior 75 years.

More recently, in a study of three coastal stations in southern and central Greenland that possess almost uninterrupted temperature records between 1950 and 2000, Chylek *et al.* (2004) discovered that "summer temperatures, which are most relevant to Greenland ice sheet melting rates, do not show any persistent increase during the last fifty years." In fact, working with the two stations with the longest records (both over a century in length), they determined that coastal Greenland's peak temperatures occurred between 1930 and 1940, and that the subsequent decrease in temperature was so substantial and sustained that then-current coastal temperatures were "about  $1^{\circ}\text{C}$  below their 1940 values." Furthermore, they note that "at the summit of the Greenland ice sheet the summer average temperature has decreased at the rate of  $2.2^{\circ}\text{C}$  per decade since the beginning of the measurements in 1987."

At the *start* of the 20th century, however, Greenland *was* warming, as it emerged, along with the rest of the world, from the depths of the Little Ice Age. What is more, between 1920 and 1930, when the atmosphere's  $\text{CO}_2$  concentration rose by a mere 3 to 4 ppm, there was a *phenomenal* warming at all five coastal locations for which contemporary temperature records are available. In fact, in the words of Chylek *et al.*, "average annual temperature rose between 2 and  $4^{\circ}\text{C}$  [and by as much as  $6^{\circ}\text{C}$  in the winter] in less than ten years." And this warming, as they note, "is also seen in the  $^{18}\text{O}/^{16}\text{O}$  record of the Summit ice core (Steig *et al.*, 1994; Stuiver *et al.*, 1995; White *et al.*, 1997)."

In commenting on this dramatic temperature rise, which they call the *great Greenland warming of the 1920s*, Chylek *et al.* conclude that "since there was no significant increase in the atmospheric greenhouse gas concentration during that time, the Greenland warming of the 1920s demonstrates that a large and rapid temperature increase can occur over Greenland, and perhaps in other regions of the Arctic, due to internal climate variability such as the NAM/NAO [Northern Annular Mode/North Atlantic Oscillation], without a significant anthropogenic influence."

In light of these several real-world observations, it is clear that the recent upswing in glacial activity on Greenland likely has had nothing to do with anthropogenic-induced global warming, as temperatures there have yet to rise either as *fast* or as *high* as they did during the great warming of the 1920s, which was clearly a *natural* phenomenon. It is also important to recognize the fact that coastal glacial discharge represents only *half* of the equation relating to sea level change, the other half being inland ice accumulation derived from precipitation; and

when the mass balance of the *entire* Greenland ice sheet was recently assessed via satellite radar altimetry, quite a different result was obtained than that suggested by the seven *Science* papers of 24 March.

Zwally *et al.* (2005), for example, found that although "the Greenland ice sheet is thinning at the margins," it is "growing inland with a small overall mass gain." In fact, for the 11-year period 1992-2003, Johannessen *et al.* (2005) found that "below 1500 meters, the elevation-change rate is [a negative]  $2.0 \pm 0.9$  cm/year, in qualitative agreement with reported thinning in the ice-sheet margins," but that "an increase of  $6.4 \pm 0.2$  cm/year is found in the vast interior areas above 1500 meters." Spatially averaged over the bulk of the ice sheet, the net result, according to the latter researchers, was a mean increase of  $5.4 \pm 0.2$  cm/year, "or ~60 cm over 11 years, or ~54 cm when corrected for isostatic uplift." Consequently, the Greenland ice sheet would appear to have experienced no net loss of mass over the last decade for which data are available. Quite to the contrary, in fact, it was likely host to a net *accumulation* of ice, which Zwally *et al.* found to be producing a  $0.03 \pm 0.01$  mm/year *decline* in sea-level.

In an attempt to downplay the significance of these inconvenient findings, Kerr quoted Zwally as saying he believes that "right now" the Greenland ice sheet is experiencing a net loss of mass. Why? Kerr says Zwally's belief is "based on his gut feeling about the most recent radar and laser observations." Fair enough. But *gut feelings* are a poor substitute for comprehensive real-world measurements; and even if the things that Zwally's intestines were telling him are ultimately found to be correct, their confirmation would only demonstrate just how rapidly the Greenland environment can change. Also, we would have to wait and see how long the mass losses prevailed in order to assess their significance within the context of the CO<sub>2</sub>-induced global warming debate. For the present and immediate future, therefore, we have no choice but to stick with what existent data and analyses suggest, i.e., that *cumulatively since the early 1990s* and *conservatively* (since the balance is likely still positive), there has been no net loss of mass from the Greenland ice sheet.

Nevertheless, many continue to hold to the view that the Greenland Ice Sheet is teetering on the verge of extinction, that it will melt rapidly and all but "slip-sliding away" into the ocean, where its unleashed water will raise global sea levels to heights that will radically alter continental coastlines and submerge major cities. The recent study of Eldrett *et al.* (2007), however, provides further new evidence that such an alarmist view of the matter is poles away from the truth.

The five researchers from the School of Ocean and Earth Science of the National Oceanography Centre of the University of Southampton in the UK report they "have generated a new stratigraphy for three key Deep Sea Drilling Project/Ocean Drilling Program sites by calibrating dinocyst events to the geomagnetic polarity timescale." In doing so, they say their detailed core observations revealed evidence for "extensive ice-rafted debris, including macroscopic dropstones, in late Eocene to early Oligocene sediments from the Norwegian-Greenland Sea that were deposited between about 38 and 30 million years ago." They further report that their data "indicate sediment rafting by glacial ice, rather than sea ice, and point to East Greenland

as the likely source," and they conclude that their data thus suggest "the existence of (at least) isolated glaciers on Greenland about 20 million years earlier than previously documented." What is particularly interesting about this finding, as Eldrett *et al.* describe it, is that it indicates the presence of glacial ice on Greenland "at a time when temperatures and atmospheric carbon dioxide concentrations were substantially higher." How much higher? According to graphs the researchers present, ocean bottom-water temperatures were 5-8°C warmer, while atmospheric CO<sub>2</sub> concentrations were as much as *four times greater than they are today*.

The problem these observations provide for those who hold to the view that global warming will melt the Greenland ice sheet, to quote Eldrett *et al.*, is that "palaeoclimate model experiments generate substantial ice sheets in the Northern Hemisphere for the Eocene only in runs where carbon dioxide levels are lower (approaching the pre-anthropogenic level) than suggested by proxy records," which records indicate atmospheric CO<sub>2</sub> concentrations fully *two to seven times greater than the pre-anthropogenic level* during the time of the newly-detected ice sheets.

"Regardless," as the researchers say, their data "provide the first stratigraphically extensive evidence for the existence of continental ice in the Northern Hemisphere during the Palaeogene," which "is about 20 million years earlier than previously documented, at a time when global deep water temperatures and, by extension, surface water temperatures at high latitude, were much warmer." Therefore - and also "by extension" - there is great reason to not only *doubt*, but to *reject out-of-hand*, scare stories of sea levels rapidly rising tens of feet in response to a predicted rapid demise of the Greenland Ice Sheet, which is seen by the alarmists as occurring in response to a warming of the planet that may be pushing it perilously close to a high-temperature "tipping point," for we now have evidence of a *much* warmer period of time that *failed* to bring about such a catastrophic consequence.

Other evidence that contradicts climate-alarmist contentions of the impending demise of the Greenland Ice Sheet has been around for several years. Cuffey and Marshall (2000), for example, reevaluated previous estimates of the Greenland Ice Sheet's contribution to sea level rise during the last interglacial (a rise of one to two meters), based on a recalibration of oxygen-isotope-derived temperatures from central Greenland ice cores. The results of their analysis suggested that the Greenland Ice Sheet was much smaller during the last interglacial than had previously been thought, with melting of the ice sheet contributing somewhere between four and five and a half meters to sea level rise. Although these results suggest that wastage of the Greenland Ice Sheet could potentially raise sea levels considerably more than had previously been believed, Hvidberg (2000) put a positive spin on the subject by stating that "high sea levels during the last interglacial should not be interpreted as evidence for extensive melting of the West Antarctic Ice Sheet, and so challenges the hypothesis that the West Antarctic is particularly sensitive to climate change," which is *good* news, as West Antarctica presents a much greater threat to global sea level rise than does Greenland. Also, whereas the possibility exists that sea levels in the present interglacial could yet rise to the heights of those of the last interglacial as a result of a major shrinking of the Greenland Ice Sheet, Cuffey and Marshall estimate that the ice sheet's widespread melting during the prior interglacial took place over

the course of a few *millennia*, as opposed to the *decades* that could be counted on one's hands and toes that are suggested by alarmist scaremongering.

Continuing, Krabill *et al.* (2000) used data obtained from aircraft laser-altimeter surveys over northern Greenland in 1994 and 1999, together with previously reported data from southern Greenland, to evaluate the mass balance of the Greenland Ice Sheet. Above an elevation of 2000 meters they found areas of both thinning and thickening; and these phenomena nearly balanced each other, so that in the south there was a net thinning of  $11 \pm 7$  mm/year, while in the north there was a net thickening of  $14 \pm 7$  mm/year. Altogether, the entire region exhibited a net thickening of  $5 \pm 5$  mm/year; but in correcting for bedrock uplift, which averaged 4 mm/year in the south and 5 mm/year in the north, the average thickening rate decreased to *practically nothing*. In fact, the word used by Krabill *et al.* to describe the net balance was "zero."

At lower elevations, thinning was found to predominate along approximately 70% of the coast. Here, however, flight lines were few and far between, so few and far between, in fact, that the researchers said that "in order to extend our estimates to the edge of the ice sheet in areas not bounded by our surveys, we *calculated* [our italics] a *hypothetical* [our italics] thinning rate on the basis of the coastal positive degree day anomalies." Then, they *interpolated* between this calculated coastal thinning rate and the nearest observed elevation changes to obtain their final answer: a total net reduction in ice volume of  $51 \text{ km}^3/\text{year}$ .

Unfortunately, it is hard to know what *estimates* derived from *interpolations* based on *calculations* of a *hypothetical* thinning rate mean. Hence, we question their significance; and, in fact, the commentary of the researchers themselves tends to do the same. They note, for example, that they do not have a "satisfactory explanation" for the "widespread thinning at elevations below 2000 m," which suggests, to us at least, that the reason this phenomenon is unexplainable is that it may not be real. Furthermore, they note that even if the thinning was real, it could not be due to global or regional warming; for they report that Greenland temperature records indicate "the 1980s and early 1990s were about half a degree cooler than the 96-year mean."

After discussing some other factors that could possibly be involved, Krabill *et al.* state they are left with changes in ice dynamics as the most likely cause of the hypothetical ice sheet thinning. But they admit in their final sentence that "we have no evidence for such changes, and we cannot explain why they should apply to many glaciers in different parts of Greenland." Hence, it would seem that the logical thing to do is admit that this study resolves almost nothing about the mass balance of the coastal regions of the Greenland Ice Sheet, and that it resolves *absolutely* nothing about the subject of global warming and its effect or non-effect upon this hypothetical phenomenon.

In a preliminary step required to better understand the relationship of glacier dynamics to climate change in West Greenland, Taurisano *et al.* (2004) described the temperature trends of the Nuuk fjord area during the last century. This analysis of all pertinent regional data led them

to conclude that "at all stations in the Nuuk fjord, both the annual mean and the average temperature of the three summer months (June, July and August) exhibit a pattern in agreement with the trends observed at other stations in south and west Greenland (Humlum 1999; Hanna and Cappelen, 2003)." As they describe it, the temperature data "show that a warming trend occurred in the Nuuk fjord during the first 50 years of the 1900s, followed by a cooling over the second part of the century, when the average annual temperatures decreased by approximately 1.5°C." Coincident with this cooling trend there was also what they describe as "a remarkable increase in the number of snowfall days (+59 days)." What is more, they report that "not only did the cooling affect the winter months, as suggested by Hanna and Cappelen (2002), but also the summer mean," noting that "the summer cooling is rather important information for glaciological studies, due to the ablation-temperature relations." Last of all, they report there was no significant trend in annual precipitation.

In their concluding discussion, Taurisano *et al.* remark that the temperature data they studied "reveal a pattern which is common to most other stations in Greenland." Hence, we can be thankful that whatever the rest of the Northern Hemisphere may be doing, *the part that holds the lion's share of the hemisphere's ice has been cooling for the past half-century*, and at a very significant rate, making it ever more unlikely that its horde of frozen water will be released to the world's oceans to raise havoc with global sea level any time soon. In addition, because the annual number of snowfall days over much of Greenland has increased so dramatically over the same time period, it is possible that enhanced accumulation of snow on its huge ice sheet may be compensating for the melting of many of the world's mountain glaciers and keeping global sea level in check for this reason too. Last of all, Greenland's temperature trend of the past half-century has been just the *opposite* - and strikingly so - of that which is claimed for the Northern Hemisphere and the world by the IPCC and its climate-alarmist friends. Furthermore, as Greenland contributes significantly to the land area of the Arctic, it presents these folks with a *double* problem, as they have historically claimed that high northern latitudes should be the first to exhibit convincing evidence of CO<sub>2</sub>-induced global warming.

In a study with a negative take on the issue, Rignot and Kanagaratnam (2005) used satellite radar interferometry observations of Greenland to detect what they described as "widespread glacier acceleration." Calculating that this phenomenon had led to a doubling of the ice sheet mass deficit in the last decade and, therefore, a comparable increase in Greenland's contribution to rising sea levels, they went on to claim that "as more glaciers accelerate ... the contribution of Greenland to sea-level rise will continue to increase."

With respect to these contentions, we have no problem with what the two researchers have *observed* with respect to Greenland's glaciers; but we feel compelled to note that what they have *calculated* with respect to the mass balance of Greenland's Ice Sheet and what they say it implies about sea level are diametrically opposed to the story told by other more inclusive real-world data. One reason for this discrepancy is that instead of relying on *measurements* for this evaluation, Rignot and Kanagaratnam relied on the *calculations* of Hanna *et al.* (2005), who used *meteorological models* "to retrieve annual accumulation, runoff, and surface mass balance." When actual *measurements* of the ice sheet via satellite radar altimetry are

employed, for example, a decidedly different perspective is obtained, as indicated by the work of Zwally *et al.* (2005) and Johannessen *et al.* (2005), which we cited earlier in this Summary. Consequently, and in direct contradiction of the claim of Rignot and Kanagaratnam, Greenland would appear to have experienced no ice sheet mass deficit in the last decade. Quite to the contrary, in fact, it has likely been host to a net *accumulation* of ice, which Zwally *et al.* estimate to be contributing a negative  $0.03 \pm 0.01$  mm/year to sea-level change. As a result, the net accumulation of ice on Greenland over the past decade or more may well have been ever so slightly *lowering* global sea level.

Yet in spite of all the real-world evidence that supports this positive perspective, climate alarmists such as Al Gore continue to claim that *if Greenland melted or broke up and slipped into the sea .. sea levels worldwide would increase by between 18 and 20 feet* (Gore, 2006). Quoting politicians like the UK's Sir David King, who says "the maps of the world will have to be redrawn," Gore conveys the impression that the occurrence of this hypothetical scenario is something we could expect to witness in the very near future. And to make this point even more poignant, Gore illustrates in his *An Inconvenient Truth* book what would likely happen to Florida, San Francisco Bay, the Netherlands, Beijing, Shanghai, Calcutta, Bangladesh and Manhattan if this were to occur, suggesting that we should begin combating now what he implies is a *serious threat* commensurate with other major present-day concerns. The perspective provided by real-world science, however, is something far different, as the materials we have reviewed above clearly demonstrate, and as the findings of yet another analysis of the subject indicate as well.

In the 16 March 2007 issue of *Science*, which highlights the current status of polar-region science at the start of the International Polar Year, Shepherd and Wingham (2007) review what is known about sea-level contributions arising from wastage of the Antarctic and Greenland Ice Sheets, concentrating on the results of 14 satellite-based estimates of the imbalances of the polar ice sheets that have been derived since 1998. These studies have been of three major types - standard mass budget analyses, altimetry measurements of ice-sheet volume changes, and measurements of the ice sheets' changing gravitational attraction - and they have yielded a diversity of values, ranging from a sea-level-rise-equivalent of 1.0 mm/year to a sea-level-fall-equivalent of 0.15 mm/year.

Of these three approaches, the results of the latter technique, according to Shepherd and Wingham, "are more negative than those provided by mass budget or altimetry." Why? Because, in their words, the gravity-based technique "is new, and [1] a consensus about the measurement errors has yet to emerge, [2] the correction for postglacial rebound is uncertain, [3] contamination from ocean and atmosphere mass changes is possible, and [4] the results depend on the method used to reduce the data." In addition, they say that (5) the Gravity Recovery and Climate Experiment (GRACE) record is only three years long, and that (6) it is thus particularly sensitive to short-term fluctuations in ice sheet behavior that may not be indicative of what is occurring over a much longer timeframe. Even including these likely-inflated results, however, the two researchers conclude that the current "best estimate" of the contribution of polar ice wastage (from both Greenland *and* Antarctica) to global sea level change is a rise of

0.35 millimeters per year, which over a *century* amounts to only 35 millimeters *or* - to better compare it to the 20-foot rise described by Gore - *a little less than an inch and a half*.

Yet even this unimpressive sea level increase may be way too large, for although two of Greenland's largest outlet glaciers doubled their rates of mass loss in less than a year in 2004 - causing climate alarmists to claim the Greenland Ice Sheet was responding much more rapidly to global warming than anyone had ever expected - Howat *et al.* (2007) report that the two glaciers' rates of mass loss "decreased in 2006 to near the previous rates." And these observations, in their words, "suggest that special care must be taken in how mass-balance estimates are evaluated, particularly when extrapolating into the future, because short-term spikes could yield erroneous long-term trends."

In light of these many observations, we feel it should be obvious that much more is often implied about the future behavior of the Greenland Ice Sheet and its impact on global sea level than is scientifically justified. In fact, *vastly* more than is justified is often implied.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/s/sealevelgreenland.php>.

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## **4.6. Antarctica**

Additional information on this topic, including reviews on Antarctica not discussed in this section, can be found at [http://www.co2science.org/subject/a/subject\\_a.php](http://www.co2science.org/subject/a/subject_a.php) under the heading Antarctica.

### **4.6.1. Temperature**

The study of Antarctic temperatures has provided valuable insight and spurred contentious debate on issues pertaining to global climate change. Key among the pertinent findings has been the observation of a large-scale correlation between proxy air temperature and atmospheric CO<sub>2</sub> measurements obtained from ice cores drilled in the interior of the continent. In the mid- to late-1980s, this broad correlation dominated much of the climate change debate;

and many jumped on the global warming bandwagon, saying the gross CO<sub>2</sub>-temperature correlation proved that changes in atmospheric CO<sub>2</sub> concentration caused changes in air temperature, and that future increases in the air's CO<sub>2</sub> content due to anthropogenic CO<sub>2</sub> emissions would therefore intensify global warming.

By the late 1990s and early 2000s, however, the bottom began to fall out of the poorly constructed bandwagon, as the evidentiary glue that held it together began to weaken. Advances in ice-coring instrumentation and techniques had improved considerably, and newer studies with finer temporal resolution began to reveal that, if anything, increases (decreases) in air temperature drive increases (decreases) in atmospheric CO<sub>2</sub> content, and not vice versa [see Indermuhle *et al.* (2000), Monnin *et al.* (2001)]. Thus, a severe blow was dealt to the climate-alarmist community, as a major tenant of the CO<sub>2</sub>-induced global warming hypothesis was shown to be contradicted by real-world observations.

The most recent of these studies (Caillon *et al.*, 2003) demonstrates that during Glacial Termination III, "the CO<sub>2</sub> increase lagged Antarctic deglacial warming by  $800 \pm 200$  years." This finding, in their words, "confirms that CO<sub>2</sub> is not the forcing that initially drives the climatic system during a deglaciation."

In spite of this admission, Caillon *et al.*, and many others, hold to the view that the subsequent increase in atmospheric CO<sub>2</sub> -- which is believed to be due to warming-induced CO<sub>2</sub> outgassing from the world's oceans -- serves to amplify the warming that is caused by whatever prompts the temperature to rise in the first place. This belief, however, is founded on unproven assumptions about the strength of CO<sub>2</sub>-induced warming; and it is applied without any regard for biologically-induced negative climate feedbacks that may occur in response to atmospheric CO<sub>2</sub> enrichment [see the Chapter on Feedback Factors in this report].

A second major blow to the CO<sub>2</sub>-induced global warming hypothesis comes from the instrumental temperature record of the more recent past. This second setback is manifested in the contradiction between observed and model-predicted Antarctic temperature trends of the past several decades. According to nearly all climate models, CO<sub>2</sub>-induced global warming should be most evident in earth's polar regions; but analyses of Antarctic near-surface and tropospheric air temperatures tell a radically different story.

Doran *et al.* (2002), for example, examined temperature trends in the McMurdo Dry Valleys of Antarctica over the period 1986 to 2000, reporting a phenomenal cooling rate of approximately 0.7°C per decade. This dramatic rate of cooling, they state, "reflects longer term continental Antarctic cooling between 1966 and 2000." In addition, the 14-year temperature decline in the dry valleys occurred in the summer and autumn, just as most of the 35-year cooling over the continent as a whole (which did not include any data from the dry valleys) also occurred in the summer and autumn.

In another study, Comiso (2000) assembled and analyzed Antarctic temperature data obtained from 21 surface stations and from infrared satellites operating since 1979. They found that for

all of Antarctica, temperatures had declined by 0.08°C and 0.42°C per decade, respectively, when assessed via these two data sets. And in yet another study, Thompson and Solomon (2002) also report a cooling trend for the interior of Antarctica.

In spite of the decades-long cooling that has been observed for the continent as a whole, one region of Antarctica has actually bucked the mean trend and *warmed* over the same time period: the Antarctic Peninsula/Bellingshausen Sea region. But is the temperature increase that has occurred there evidence of CO<sub>2</sub>-induced global warming?

No. According to Vaughan *et al.* (2001), "rapid *regional* warming [our italics]" has led to the loss of seven ice shelves in this region during the past 50 years. However, they note that sediment cores from 6000 to 1900 years ago suggest the Prince Gustav Channel Ice Shelf - which collapsed in this region in 1995 - "was absent and climate was as warm as it has been recently," when, of course there was much less CO<sub>2</sub> in the air.

Although it is tempting for climate alarmists to cite the 20th century increase in atmospheric CO<sub>2</sub> concentration as the cause of the recent regional warming, "to do so without offering a mechanism," say Vaughan *et al.*, "is superficial." And so it is, as the recent work of Thompson and Solomon (2002) suggests that much of the warming can be explained by "a systematic bias toward the high-index polarity of the SAM," or Southern Hemispheric Annular Mode, such that the ring of westerly winds encircling Antarctica has recently been spending more time in its strong-wind phase.

This is also the conclusion of Kwok and Comiso (2002), who report that over the 17-year period 1982-1998, the SAM index shifted towards more positive values (0.22/decade), noting that a positive polarity of the SAM index "is associated with cold anomalies over most of Antarctica with the center of action over the East Antarctic plateau." At the same time, the SO index shifted in a negative direction, indicating "a drift toward a spatial pattern with warmer temperatures around the Antarctic Peninsula, and cooler temperatures over much of the continent." Together, the authors say the positive trend in the *coupled* mode of variability of these two indices (0.3/decade) represents a "significant bias toward positive polarity" that they describe as "remarkable."

Kwok and Comiso additionally report that "the tropospheric SH annular mode has been shown to be related to changes in the lower stratosphere (Thompson and Wallace, 2000)," noting that "the high index polarity of the SH annular mode is associated with the trend toward a cooling and strengthening of the SH stratospheric polar vortex during the stratosphere's relatively short active season in November," which is pretty much the same theory that has been put forth by Thompson and Solomon (2002).

In another slant on the issue, Yoon *et al.* (2002) report that "the maritime record on the Antarctic Peninsula shelf suggests close chronological correlation with Holocene glacial events in the Northern Hemisphere, indicating the possibility of coherent climate variability in the Holocene." In the same vein, Khim *et al.* (2002) say that "two of the most significant climatic

events during the late Holocene are the Little Ice Age (LIA) and Medieval Warm Period (MWP), both of which occurred globally (Lamb, 1965; Grove, 1988)," noting further that "evidence of the LIA has been found in several studies of Antarctic marine sediments (Leventer and Dunbar, 1988; Leventer *et al.*, 1996; Domack *et al.*, 2000)."

To this list of scientific journal articles documenting the existence of the LIA in Antarctica can now be added Khim *et al.*'s own paper, which also demonstrates the presence of the MWP in Antarctica, as well as earlier cold and warm periods of similar intensity and duration. Hence, it is getting ever more difficult for climate alarmists to continue claiming that these several-hundred-year cold and warm periods were confined to lands bordering the North Atlantic Ocean. They clearly were *global*; and they clearly demonstrate the reality of the likely solar-induced millennial-scale climatic oscillation that is manifest in the post-1850 warming of the world that climate alarmists misconstrue as having been caused by the concomitant rise in the air's CO<sub>2</sub> content.

Further evidence that the Antarctic as a whole is in the midst of a cooling trend comes from the study of Watkins and Simmonds (2000), who analyzed region-wide changes in sea ice. Reporting on trends in a number of Southern Ocean sea ice parameters over the period 1987 to 1996, they found statistically significant increases in sea ice area and total sea ice extent, as well as an increase in sea ice season length since the 1990s. Combining these results with those from a previous study revealed these trends to be consistent back to at least 1978. And in another study of Antarctic sea ice extent, Yuan and Martinson (2000) report that the net trend in the mean Antarctic ice edge over the last 18 years has been an equatorward expansion of 0.011 degree of latitude per year.

When all is said and done, therefore, the temperature history of Antarctica provides no evidence for the CO<sub>2</sub>-induced global warming hypothesis. In fact, it argues strongly against it. But what if the Antarctic *were* to warm as a result of some natural or anthropogenic-induced change in earth's climate? What would the consequences be? For one thing, it would likely help to increase both the number and diversity of penguin species (Sun *et al.*, 2000; Smith *et al.*, 1999), and it would also tend to increase the size and number of populations of the continent's only two vascular plant species (Xiong *et al.*, 2000). With respect to the continent's great ice sheets, there would not be much of a problem either, as not even a warming event as dramatic as 10°C is predicted to result in a net change in the East Antarctic Ice Sheet (Näslund *et al.*, 2000), which suggests that predictions of catastrophic coastal flooding due to the melting of the world's polar ice sheets are way off the mark when it comes to representing reality.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/a/antarcticatemp.php>.

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#### 4.6.2. Contribution to Sea Level

Vaughn *et al.* (1999) used more than 1800 published and unpublished *in situ* measurements of the surface mass balance of Antarctica to produce an assessment of yearly ice accumulation over the continent. Their results indicated that the "total net surface mass balance for the conterminous grounded ice sheet is 1811 Gton yr<sup>-1</sup> (149 kg m<sup>-2</sup> yr<sup>-1</sup>) and for the entire ice sheet including ice shelves and embedded ice rises, 2288 Gton yr<sup>-1</sup> (166 kg m<sup>-2</sup> yr<sup>-1</sup>)." These values, in their words, "are around 18% and 7% higher than the estimates widely adopted at present [1999]," which were derived about 15 years earlier. Hence, they suggest that net icefall on Antarctica may well have increased somewhat over that prior decade and a half. Nevertheless,

because of uncertainties in the various numbers, Vaughn *et al.* say "we are still unable to determine even the sign of the contribution of the Antarctic Ice Sheet to recent sea level change," which suggests the Antarctic canary has not a clarity of mind on the matter and is somewhat befuddled.

In another review of the subject that was published about the same time, Reeh (1999) found a broad consensus for the conclusion that a 1°C warming would create but little net change in mean global sea level; for Greenland's contribution would be a sea level rise on the order of 0.30 to 0.77 millimeters per year, while *Antarctica's contribution would be a fall on the order of 0.20 to 0.70 millimeters per year*, which also suggests the Antarctic canary is rather confused.

The following year, Wild and Ohmura (2000) studied the mass balance of Antarctica using two general circulation models developed at the Max Plank Institute for Meteorology in Hamburg, Germany: the older ECHAM3 and the new and improved ECHAM4. Under a doubled atmospheric CO<sub>2</sub> scenario, the two models were in close agreement in their mass balance projections, with both of them predicting *increases in ice sheet growth*, indicative of *decreases in sea level*, which by this time had the Antarctic canary really bewildered.

Two years later, van der Veen (2002) addressed the problem again, noting that "for purposes of formulating policies, some of which could be unpopular or costly, it is imperative that probability density functions be derived for predicted values such as sea level rise," further stating that with "greater societal relevance comes increased responsibility for geophysical modelers to demonstrate convincingly the veracity of their models to accurately predict future evolution of the earth's natural system or particular components thereof." In stepping forward to perform this task with respect to sea level change, however, he was forced to conclude that "the validity of the parameterizations used by [various] glaciological modeling studies to estimate changes in surface accumulation and ablation under changing climate conditions has not been convincingly demonstrated." Van der Veen calculated, for example, that uncertainties in model parameters are sufficiently great to yield a 95% confidence range of projected meltwater contributions from Greenland and Antarctica that encompass global sea-level *lowering* as well as rise by 2100 A.D. for low, middle and high warming scenarios. Hence, even for the *worst* of the IPCC warming projections, there could well be little to no change in mean global sea level due to the likely rise in the air's CO<sub>2</sub> content that may occur over the rest of this century. As a result, van der Veen concludes that the confidence level that can be placed in current ice sheet mass balance models "is quite low." Paraphrasing an earlier assessment of the subject, in fact, he says that today's best models "currently reside on the lower rungs of the ladder of excellence" and that "considerable improvements are needed before accurate assessments of future sea-level change can be made," once again leaving the Antarctic canary little to do but wring its wings in frustration.

Last of all, Wadhams and Munk (2004) attempted "an independent estimate of eustatic sea level rise based on the measured freshening of the global ocean, and with attention to the contribution from melting of sea ice (which affects freshening but not sea level)," reporting that their analysis produces "a eustatic rise of only 0.6 mm/year" and that when a steric contribution of 0.5 mm/year is added to the eustatic component, "a total of 1.1 mm/year,



somewhat less than IPCC estimates," is the final result. Perhaps the most interesting finding of their analysis, however, is that the continental run-off which is "allowed," after subtracting the effect of sea ice melt, "is considerably lower than current estimates of sub-polar glacial retreat, suggesting a negative contribution from polar ice sheets (Antarctica plus Greenland) or from other non-glacial processes." In this regard, they assert "we do not have good estimates of the mass balance of the Antarctic ice sheet, which could make a much larger positive *or negative* [our italics] contribution."

The bottom line of Wadhams and Munk's analysis, as well as those of the other studies we have reviewed, clearly suggests - in fact *states* - there is considerable uncertainty associated with a number of basic parameters that are related to the water balance of the world's oceans and the meltwater contribution of Antarctica; and until these uncertainties are satisfactorily resolved, we - like the Antarctic canary - cannot be confident that we know what is happening at the bottom of the world in terms of phenomena related to the vertical displacement of the upper surface of the world's oceans. In fact, we haven't really a clue.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/a/antarcticasealvl.php> and <http://www.co2science.org/subject/s/sealevelantarctica.php>.

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### 4.6.3. West Antarctic Ice Sheet

Additional information on this topic, including reviews the West Antarctic Ice Sheet not discussed here, can be found at [http://www.co2science.org/subject/w/subject\\_w.php](http://www.co2science.org/subject/w/subject_w.php) under the heading West Antarctic Ice Sheet.

#### 4.6.3.1. Collapse and Disintegration

The West Antarctic Ice Sheet (WAIS) is often described as the world's most *unstable* large ice sheet. As Hillenbrand *et al.* (2002) report, "it was speculated, from observed fast grounding-line retreat and thinning of a glacier in Pine Island Bay (Rignot, 1998; Shepherd *et al.*, 2001), from the timing of late Pleistocene-Holocene deglaciation in the Ross Sea (Bindschadler, 1998; Conway *et al.*, 1999), and from predicted activity of ice-stream drainage in response to presumed future global warming (Oppenheimer, 1998), that the WAIS may disappear in the future, causing the sea-level to rise at a rate of 1 to 10 mm/year (Bindschadler, 1998; Oppenheimer, 1998)." Hence, it is important to keep an eye on what is written about the subject in the scientific literature, which is what we do as ever more pertinent papers are published, the findings of a number of which we review in this section as they pertain to potential WAIS collapse and disintegration.

Cofaigh *et al.* (2001) analyzed five sediment cores from the continental rise west of the Antarctic Peninsula and six from the Weddell and Scotia Seas for their ice rafted debris (IRD) content, in an attempt to see if there are Antarctic analogues of the Heinrich layers of the North Atlantic Ocean, which testify of the repeated collapse of the eastern margin of the Laurentide Ice Sheet and the concomitant massive discharge of icebergs. If such IRD layers exist around Antarctica, the researchers reasoned, they would be evidence of "periodic, widespread catastrophic collapse of basins within the Antarctic Ice Sheet," which could obviously occur again. However, after carefully studying their data, they concluded that "the ice sheet over the Antarctic Peninsula did not undergo widespread catastrophic collapse along its western margin during the late Quaternary," and they say this evidence "argues against pervasive, rapid ice-sheet collapse around the Weddell embayment over the last few glacial cycles." And if there was no dramatic break-up of the WAIS over the last few glacial cycles, there's a very good chance there will be none before the current interglacial ends, especially since the data of Petit *et al.* (1999) indicate that the peak temperatures of each of the previous four interglacials were warmer than the peak temperature of the current interglacial ... and by an average of more than 2°C.

Hillenbrand *et al.* (2002) studied the nature and history of glaciomarine deposits contained in sediment cores recovered from the West Antarctic continental margin in the Amundsen Sea to "test hypotheses of past disintegration of the WAIS." In doing so, they found that all proxies regarded as sensitive to a WAIS collapse changed markedly during the global climatic cycles of the past 1.8 million years, but that they "do not confirm a complete disintegration of the WAIS during the Pleistocene" at a place where "dramatic environmental changes linked to such an event should be documented." In fact, they say their results "suggest relative stability rather than instability of the WAIS during the Pleistocene climatic cycles," and they note that this conclusion is "consistent with only a minor reduction of the WAIS during the last interglacial period," citing the work of Huybrechts (1990), Cuffey and Marshall (2000) and Huybrechts (2002).

In another paper that addresses the subject of possible WAIS collapse, O'Neill and Oppenheimer (2002) say the ice sheet "may have disintegrated in the past during periods only

modestly warmer ( $\sim 2^{\circ}\text{C}$  global mean) than today," and they thus claim that setting "a limit of  $2^{\circ}\text{C}$  above the 1990 global average temperature" -- above which the mean temperature of the globe should not be allowed to rise -- "is justified." If the truth be told, however, a  $2^{\circ}\text{C}$  warming of the globe would likely have *little to no impact* on the stability of the WAIS.

As we have already noted, for example, the average Antarctic peak temperature of all four of the world's prior interglacials was *at least*  $2^{\circ}\text{C}$  greater than the Antarctic peak temperature of the current interglacial; yet, in the words of the scientists who developed the pertinent temperature record (Petit *et al.*, 1999), the evidence contained in the core "makes it unlikely that the West Antarctic ice sheet collapsed during the past 420,000 years," which is pretty much the same conclusion that was drawn by Cofaigh *et al.* In addition, we know from the Vostok ice core record that the peak Antarctic temperature of the most *recent* prior interglacial was fully  $3^{\circ}\text{C}$  warmer than the peak Antarctic temperature of the interglacial in which we presently live, yet the WAIS *still* did not disintegrate during that prior time of elevated warmth. Furthermore, we know that throughout the long central portion of the current interglacial (when the most recent peak Antarctic temperature was reached), it was *much* warmer than it was in 1990, which is the year from which O'Neill and Oppenheimer's critical  $2^{\circ}\text{C}$  warming increment is measured; and this fact raises the  $3^{\circ}\text{C}$  temperature elevation of the last interglacial *relative to the global temperature of 1990* to something on the order of 4 or  $5^{\circ}\text{C}$ , for which, *again*, there was no evidence of even a *partial* WAIS disintegration.

Finally, and in spite of the current interglacial's *current* relative *coolness*, the Vostok ice core data indicate that the current interglacial has been *by far* the longest stable warm period of the entire 420,000-year record, which suggests we are probably long overdue for the next ice age to begin, and that we may not have the "5 to 50 centuries" that O'Neill and Oppenheimer suggest could be needed to bring about the WAIS disintegration subsequent to the attainment of whatever temperature in excess of 4 or  $5^{\circ}\text{C}$  above the current global mean would be needed to initiate the process. In conclusion, therefore, it would appear that the climate-alarmist vision of impending WAIS collapse and disintegration is does not match with reality.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/w/waiscollapse.php>.

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#### 4.6.3.2. Dynamics

For quite some time now, alarmists have obsessed over what they contend will be the imminent demise of the West Antarctic Ice Sheet (WAIS) if human-induced CO<sub>2</sub> emissions are not dramatically reduced. As Al Gore (2006) has phrased it, if "half of Antarctica melted or broke up and slipped into the sea, sea levels worldwide would increase by between 18 and 20 feet." But is this really about to happen? In what follows, we briefly review the findings of a number of studies of the dynamics of various components of the WAIS and what they suggest about the subject.

Writing in the journal *Science* were Bindschadler and Vornberger (1998), who utilized satellite imagery taken since 1963 to examine spatial and temporal changes of Ice Stream B, which flows into the Ross Ice Shelf. The data indicated that since that time, the ice stream's width had increased by nearly 4 kilometers, at a rate that was, in their words, an "order of magnitude faster than models have predicted." However, they reported that the *flow speed* of the ice

stream had *decreased* over this time period by about 50 percent, noting that "such high rates of change in velocity greatly complicate the calculation of mass balance of the ice sheet," and that such changes "do not resolve the overriding question of the stability of the West Antarctic Ice Sheet."

Bindschadler (1998) reviewed what was known about the WAIS for *Science* and analyzed its historical retreat in terms of its grounding line and ice front. This work revealed that from the time of the Last Glacial Maximum to the present, the retreat of the WAIS's grounding line had been faster than that of its ice front, which resulted in an expanding Ross Ice Shelf. In fact, Bindschadler reported that "the ice front now appears to be nearly stable," although its grounding line appeared to be retreating at a rate that suggested complete dissolution of the WAIS in another 4,000 to 7,000 years. Such a retreat would indeed result in a sustained sea level rise of 8 to 13 cm per century. However, even the smallest of these sea level rates-of-rise would require, according to Bindschadler, "a large negative mass balance for all of West Antarctica," and there were no broad-based data to support that scenario.

Switching from *Science* to *Nature*, Oppenheimer (1998) reviewed 122 studies that dealt with the stability of the WAIS and its effects on global sea level, concluding that "human-induced climate change may play a significant role in controlling the long-term stability of the West Antarctic Ice Sheet and in determining its contribution to sea-level change in the near future." Other of his statements, however, seemed to detract from this conclusion. He noted, for example, that the Intergovernmental Panel on Climate Change (IPCC) "estimated a zero Antarctic contribution to sea-level rise over the past century, and projected a small negative (about -1 cm) contribution for the twenty-first century." Furthermore, with respect to potential anthropogenic modification of the state and behavior of the atmosphere and ocean above and around Antarctica, he acknowledged that "measurements are too sparse to enable the observed changes to be attributed to any such [human-induced] global warming." And in the case of sea-ice extent, he admitted there appeared to not even be a modification; for he stated that "the IPCC assessment is that no trend has yet emerged."

Oppenheimer concluded his review with four scenarios of the future based upon various assumptions. One was that the WAIS will experience a sudden collapse that causes a 4-6 m sea-level rise within the coming century. However, he stated that this scenario "may be put aside for the moment, because no convincing model of it has been presented." A second scenario had the WAIS gradually disintegrating and contributing to a slow sea-level rise over two centuries, followed by a more rapid disintegration over the following 50 to 200 years. Once again, however, he noted that "progress on understanding [the] WAIS over the past two decades has enabled us to lower the relative likelihood of [this] scenario."

In another scenario, the WAIS takes 500-700 years to disappear, as it raises sea-level by 60-120 cm per century. Oppenheimer assesses the relative likelihood of this scenario to be the highest of all, "but with low confidence," as he puts it. Last of all is what occurs if ice streams slow, as a result of internal ice sheet readjustments, and the discharge of grounded ice decreases, which could well happen, even if ice shelves thin and major fast-moving glaciers do not slow. In such a

situation, he notes that "the Antarctic contribution to sea-level rise turns increasingly negative," i.e., sea level *falls*. And in commenting upon the suite of scenarios just described, Oppenheimer emphatically states that "it is not possible to place high confidence in any specific prediction about the future of WAIS."

Also writing in *Nature*, Bell *et al.* (1998) used aerogeophysical data to investigate processes that govern fast moving ice streams on the WAIS. In conjunction with various models, these data suggested a close correlation between the margins of various ice streams and the underlying sedimentary basins, which appeared to act as lubricants for the overlying ice. As a result, the seven scientists suggested that the positions of ice-stream margins and their onsets were controlled by features of the underlying sedimentary basins; and they concluded that "geological structures beneath the West Antarctic Ice Sheet have the potential to dictate the evolution of the dynamic ice system, modulating the influence of changes in the global climate system," although their work did not indicate what effect, if any, a modest rise in near-surface air temperature might have on this phenomenon.

Returning to *Science*, Rignot (1998) reported on satellite radar measurements of the grounding line of Pine Island Glacier from 1992 to 1996, which were studied to determine whether or not this major ice stream in remote West Antarctica was advancing or retreating. The data indicated that the glacier's grounding line had retreated inland at a rate of  $1.2 \pm 0.3$  kilometers per year over the four-year period of the study; and Rignot suggested that this retreat may have been the result of a slight increase in ocean water temperature. Because the study had utilized only four years of data, however, questions concerning the long-term stability of the WAIS, in the words of the researcher, "cannot be answered at present." In addition, although the glacier's grounding line had been found to be retreating, subsequent satellite images suggested that the location of the ice front had remained stable.

Finally advancing from 1998 to 1999, but still publishing in the journal *Science*, Conway *et al.* (1999) examined previously reported research, while conducting some of their own, dealing with the retreat of the WAIS since its maximum glacial extent some 20,000 years ago. In doing so, they determined that the ice sheet's grounding line remained near its maximum extent until about 10,000 years ago, whereupon it began to retreat at a rate of about 120 meters per year. This work also indicated that at the end of the 20th century it was retreating at about the same rate, which suggests that if it continues to behave as it has in the past, complete deglaciation of the WAIS will occur in about 7000 years. The researchers thus concluded that the modern-day grounding-line retreat of the WAIS is part of an ongoing recession that has been underway since the early to mid-Holocene; and that "it is not a consequence of anthropogenic warming or recent sea level rise." Consequently, climate alarmists who claim that CO<sub>2</sub>-induced global warming is responsible for every inch of WAIS retreat, as well as every iceberg that breaks free of the ice sheet, are not justified in making such claims.

Stepping another year into the future, Stenoien and Bentley (2000) mapped the catchment region of Pine Island Glacier using radar altimetry and synthetic aperture radar interferometry, which they used to develop a velocity map that revealed a system of tributaries that channel ice

from the catchment area into the fast-flowing glacier. Then, by combining the velocity data with information on ice thickness and snow accumulation rates, they were able to calculate, within an uncertainty of 30%, that the mass balance of the catchment region was not significantly different from zero.

One year later, Shepherd *et al.* (2001) used satellite altimetry and interferometry to determine the rate of change of the ice thickness of the entire Pine Island Glacier drainage basin between 1992 and 1999. This work revealed that the grounded glacier thinned by up to 1.6 meters per year between 1992 and 1999. Of this phenomenon, the researchers wrote that "the thinning cannot be explained by short-term variability in accumulation and must result from glacier dynamics," and since glacier dynamics typically respond to phenomena operating on time scales of hundreds to thousands of years, this observation would argue *against* 20th-century warming being a primary cause of the thinning. Shepherd *et al.* additionally say they could "detect no change in the rate of ice thinning across the glacier over a 7-year period," which also suggests that a long-term phenomenon of considerable inertia must be at work in this particular situation.

But what if the rate of glacier thinning, which *sounds* pretty dramatic, were to continue unabated? The researchers state that "if the trunk continues to lose mass at the present rate it will be entirely afloat within 600 years." And if that happens, they say they "estimate the net contribution to eustatic sea level to be 6 mm," which means that over each century of the foreseeable future, we could expect global sea level to rise by about one millimeter, or about the thickness of a paper clip.

Publishing in same year were Pudsey and Evans (2001), who studied ice-rafted debris obtained from four cores in Prince Gustav Channel, which until 1995 was covered by floating ice shelves. Their efforts indicated that the ice shelves had also retreated in mid-Holocene time, but that, in their words, "colder conditions after about 1.9 ka allowed the ice shelf to reform." Although they thus concluded that the ice shelves are sensitive indicators of *regional* climate change, they were careful to state that "we should not view the recent decay as an unequivocal indicator of anthropogenic climate change." Indeed, the disappearance of the ice shelves was *not unique*; it had happened before without our help, and it could well have happened again on its own. In fact, the breakup of the Prince Gustav Channel ice shelves was likely nothing more than the culmination of the Antarctic Peninsula's *natural recovery* from the cold conditions of Little Ice Age, as has been observed in many places throughout the Northern Hemisphere and several parts of the Southern Hemisphere as well.

Taking another step into the future, Raymond (2002) presented a brief appraisal of the status of the world's major ice sheets. His primary conclusions relative to the WAIS were that (1) "substantial melting on the upper surface of WAIS would occur only with considerable atmospheric warming," (2) of the three major WAIS drainages, the ice streams that drain northward to the Amundsen Sea have accelerated, widened and thinned "over substantial distances back into the ice sheet," but that "the eastward drainage toward the Weddell Sea is close to mass balance." And (3) of the westward drainage into the Ross Ice Shelf, "over the last

few centuries, margins of active ice streams migrated inward and outward," while the "overall mass balance has changed from loss to gain," as "a currently active ice stream (Whillans) has slowed by about 20% over recent decades."

In a summary statement that takes account of these observations, Raymond says that "the total mass of today's ice sheets is changing only slowly, and even with climate warming increases in snowfall should compensate for additional melting," such as might possibly occur for the WAIS if the planet's temperature continues its post-Little Ice Age rebound.

Fast-forward another year and Stone *et al.* (2003) -- working on western Marie Byrd Land -- report how they determined cosmogenic  $^{10}\text{Be}$  exposure dates of glacially-transported cobbles in elevation transects on seven peaks of the Ford Ranges between the ice sheet's present grounding line and the Clark Mountains some 80 km inland. Based on these ages and the elevations at which the cobbles were found, they reconstructed a history of ice-sheet thinning over the past 10,000-plus years. This history showed, in their words, that "the exposed rock in the Ford Ranges, up to 700 m above the present ice surface, was deglaciated within the past 11,000 years," and that "several lines of evidence suggest that the maximum ice sheet stood considerably higher than this."

Stone *et al.* additionally report that the consistency of the exposure age versus elevation trends of their data "indicates steady deglaciation since the first of these peaks emerged from the ice sheet some time before 10,400 years ago," and that the mass balance of the region "has been negative throughout the Holocene." The researchers also say their results "add to the evidence that West Antarctic deglaciation continued long after the disappearance of the Northern Hemisphere ice sheets and may still be under way," noting that the ice sheet in Marie Byrd Land "shows the same pattern of steady Holocene deglaciation as the marine ice sheet in the Ross Sea," where ice "has thinned and retreated since 7000 years ago," adding that "there is strong evidence that the limit of grounded ice in both regions -- and in Pine Island Bay -- is still receding."

As long contended by scientists who disagree with climate-alarmist claims that we are witnessing the  $\text{CO}_2$ -induced "early stages of rapid ice sheet collapse, with potential near-term impacts on the world's coastlines" -- as described by Ackert (2003) -- the work of Stone *et al.* convincingly demonstrates that the current thinning and retreat of the WAIS are merely manifestations of a slow but steady deglaciation that has been going on and on and on, ever since the beginning-of-the-end of the last great ice age. This phenomenon is unabashedly used by climate alarmists to scare people into believing anthropogenic  $\text{CO}_2$  emissions are rapidly leading to the demise of the WAIS; but Stone *et al.* say something quite different, i.e., that "the pattern of recent change is consistent with the idea that thinning of the WAIS over the past few thousand years is continuing," while Ackert makes the point even plainer, when he says that "recent ice sheet dynamics appear to be dominated by the ongoing response to deglacial forcing thousands of years ago, rather than by a recent anthropogenic warming or sea level rise."



In conclusion, the massive ice repository that is the West Antarctic Ice Sheet is *not* "slip-sliding away" and about to redefine the world's coastlines in response to rising sea levels, as contended by folks such as Al Gore and James Hansen. It seems to be behaving quite nicely, just as it has for thousands of prior years.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/w/waisdynamics.php>.

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#### 4.6.3.3. Mass Balance

Is the West Antarctic Ice Sheet (WAIS) growing or shrinking? In what follows, we briefly review the findings of several researchers who have focused their attention on the *mass balance* of the WAIS.

Anderson and Andrews (1999) analyzed grain size and foraminiferal contents of radiometrically-dated sediment cores collected from the eastern Weddell Sea continental shelf and the western Weddell Sea deep-sea floor in an attempt to better understand the behavior of both the East and West Antarctic ice sheets. In doing so, their data led them to conclude that "significant deglaciation of the Weddell Sea continental shelf took place prior to the last glacial maximum," and that the ice masses that border the Weddell Sea today "are more extensive than they were during the previous glacial minimum." Hence, they concluded "that the current interglacial setting is characterized by a more extensive ice margin and larger ice shelves than existed during the last glacial minimum, and that the modern West and East Antarctic ice sheets have not yet shrunk to their minimum." It is thus to be expected -- independent of what global air temperature may currently be doing, because of the great inertial forces at work over much longer time scales -- that the modern East and West Antarctic Ice Sheets may well continue to shrink and release more icebergs to the Southern Ocean over the coming years, decades and centuries, thereby slowly raising global sea level. Nothing man has done is responsible for these phenomena, however; and nothing man can do will impact them in any way.

Also studying the combined ice sheets of both East and West Antarctica were Wingham *et al.* (1998), who used satellite radar altimeter measurements from 1992 to 1996 to estimate the rate of change of the thickness of nearly two thirds of the grounded portion of the entire Antarctic Ice Sheet, while using snowfall variability data obtained from ice cores to ultimately calculate the mass balance of the interior of the continental ice sheet over the past century. Their results showed that, *at most*, the interior of the Antarctic Ice Sheet has been "only a modest source or sink of sea-level mass this century." As a result, Wingham *et al.* concluded that "a large century-scale imbalance for the Antarctic interior is unlikely," noting that this conclusion is in harmony with a body of relative sea-level and geodetic evidence "supporting the notion that the grounded ice has been in balance at the millennial scale." This full set of findings thus suggests that both portions of the Antarctic Ice Sheet may be rather impervious to climate changes of the magnitude characteristic of the Medieval Warm Period and Little Ice Age, which is the type of change most likely to occur -- if there is any change at all -- in response to the ongoing rise in the air's CO<sub>2</sub> content.

In another study of all of Antarctica, Vaughn *et al.* (1999) used more than 1800 published and unpublished measurements of the surface mass balance of the continent to produce an updated assessment of yearly ice accumulation. Their results indicated that the "total net surface mass balance for the conterminous grounded ice sheet is 1811 Gton yr<sup>-1</sup> (149 kg m<sup>-2</sup> yr<sup>-1</sup>) and for the entire ice sheet including ice shelves and embedded ice rises, 2288 Gton yr<sup>-1</sup> (166

kg m<sup>-2</sup> yr<sup>-1</sup>)." Since Vaughn *et al.* say "these values are around 18% and 7% higher than the estimates widely adopted at present," which were derived about 1985, they would seem to suggest that net icefall on Antarctica may well have been somewhat greater near the end of the 20th century than what was believed to have been the case a decade and a half earlier. Nevertheless, because of uncertainties in these numbers, as well as in those representing the total mass of ice lost from the ice sheet and ice shelves, the authors note that "we are still unable to determine even the sign of the contribution of the Antarctic Ice Sheet to recent sea level change."

A year later, Stenoien and Bentley (2000) mapped the catchment region of West Antarctica's Pine Island Glacier, using radar altimetry and synthetic aperture radar interferometry. These data were used to develop a velocity map that revealed a system of tributaries that channeled ice from the catchment area into the fast-flowing glacier; and by combining the velocity data with information on ice thickness and snow accumulation rates, the two researchers were able to calculate an approximate mass balance for the glacier. Within an uncertainty of 30%, it was thereby determined that the mass balance of the catchment region was not significantly different from zero.

After three more years, Davis and Ferguson (2004) evaluated elevation changes of the entire Antarctic ice sheet over the five-year period June 1995 to April 2000, based on more than 123 million elevation change measurements made by the European Space Agency's European Remote Sensing 2 satellite radar altimeter. In doing so, they determined that the east Antarctic ice sheet had a five-year trend of  $1.0 \pm 0.6$  cm/year, that the west Antarctic ice sheet had a five-year trend of  $-3.6 \pm 1.0$  cm/year, and that the entire Antarctic continent (north of 81.6°S) had a five-year trend of  $0.4 \pm 0.4$  cm/year. In addition, the Pine Island, Thwaites, DeVicq and Land glaciers of West Antarctica exhibited five-year trends ranging from - 26 to - 135 cm/year.

In discussing their findings, Davis and Ferguson noted that the strongly negative trends of the coastal glacier outlets "suggest that the basin results are due to dynamic changes in glacier flow," and that recent observations "indicate strong basal melting, caused by ocean temperature increases, is occurring at the grounding lines of these outlet glaciers." Hence, they concluded "there is good evidence that the strongly negative trends at these outlet glaciers, the mass balance of the corresponding drainage basins, and the overall mass balance of the west Antarctic ice sheet may be related to increased basal melting caused by ocean temperature increases." Nevertheless, driven by the significantly positive trend of the much larger east Antarctic ice sheet, the ice volume of the entire continent grew ever larger over the last five years of the 20th century, the majority of which increase, according to Davis and Ferguson, was due to increased snowfall.

One year later, in an Editorial Essay published in the journal *Climatic Change*, Oppenheimer and Alley (2005) discussed "the degree to which warming can affect the rate of ice loss by altering the mass balance between precipitation rates on the one hand, and melting and ice discharge to the ocean through ice streams on the other," with respect to the WAIS and Greenland Ice Sheet (GIS). After a brief overview of the topic, they noted that "the key questions with respect

to both WAIS and GIS are: What processes limit ice velocity, and how much can warming affect those processes?" In answer to these questions, they said that "no consensus has emerged about these issues nor, consequently, about the fate of either ice sheet, a state of affairs reflecting the weakness of current models and uncertainty in paleoclimatic reconstructions."

After a cursory review of the science related to these two key questions, Oppenheimer and Alley say their review "leads to a multitude of questions with respect to the basic science of the ice sheets," which we list below. However, instead of listing them in their original question form, we post them in the form of statements that address what *we do not know* about the various sub-topics mentioned, which is obviously what prompts the questions in the first place and validates the content of the statements.

- (1) *We do not know* if the apparent response of glaciers and ice streams to surface melting and melting at their termini (e.g., ice shelves) could occur more generally over the ice sheets.
- (2) *We do not know* if dynamical responses are likely to continue for centuries and propagate further inland or if it is more likely that they will be damped over time.
- (3) *We do not know* if surface melting could cause rapid collapse of the Ross or Filchner-Ronne ice shelves, as occurred for the smaller Larsen ice shelf.
- (4) *We do not know* if ice sheets made a significant net contribution to sea level rise over the past several decades.
- (5) *We do not know* what might be useful paleoclimate analogs for sea level and ice sheet behavior in a warmer world.
- (6) *We do not know* the reliability of Antarctic and Southern Ocean temperatures (and polar amplification) that are projected by current GCMs, nor do we know why they differ so widely among models, nor how these differences might be resolved.
- (7) *We do not know* the prospects for expanding measurements and improving models of ice sheets nor the timescales involved.
- (8) *We do not know* if current uncertainties in future ice sheet behavior can be expressed quantitatively.
- (9) *We do not know* what would be useful early warning signs of impending ice sheet disintegration nor when these might be detectable.
- (10) *We do not know*, given current uncertainties, if our present understanding of the vulnerability of either the WAIS or GIS is potentially useful in defining "dangerous anthropogenic interference" with earth's climate system.
- (11) *We do not know* if the concept of a threshold temperature is useful.
- (12) *We do not know* if either ice sheet seems more vulnerable and thus may provide a more immediate measure of climate "danger" and a more pressing target for research.
- (13) *We do not know* if any of the various temperatures proposed in the literature as demarking danger of disintegration for one or the other ice sheet are useful in contributing to a better understanding of "dangerous anthropogenic interference."
- (14) *We do not know* on what timescale future learning might affect the answers to these questions.

In concluding their essay, Oppenheimer and Alley describe this list of deficiencies in our knowledge of things related to the WAIS as "gaping holes in our understanding" that "will not be closed unless governments provide adequate resources for research," which seem just a bit self-serving. More importantly, however, they state that "if emissions of the greenhouse gases are not reduced while uncertainties are being resolved, there is a risk of making ice-sheet disintegration nearly inevitable."

Clearly, there is a chance -- be it ever so small -- that almost anything *could* occur. But how *probable* are such high-risk phenomena? To claim, as Oppenheimer and Alley do, that ice-sheet disintegration is *nearly inevitable* if emissions of greenhouse gases are not reduced, is *incredibly illogical*, especially in light of the existence of what they say are "gaping holes in our understanding," as enumerated in the above list. In fact, given the degree of deficiency in our knowledge of the matter, it is perhaps as likely as not that a continuation of the planet's recovery from the relative cold of the Little Ice Age could actually lead to a *buildup* of polar ice; but there is no way *we* would ever say that that outcome is "nearly inevitable."

The following year also saw the publication of a paper that had little to recommend its main conclusions. Velicogna and Wahr (2006) used measurements of time-variable gravity from the Gravity Recovery and Climate Experiment (GRACE) satellites to determine mass variations of the Antarctic ice sheet for the 34 months between April 2002 and August 2005. When all was said and done -- which included a lot of dubious approximations -- the two researchers concluded that "the ice sheet mass decreased significantly, at a rate of  $152 \pm 80 \text{ km}^3/\text{year}$  of ice, equivalent to  $0.4 \pm 0.2 \text{ mm}/\text{year}$  of global sea level rise," all of which mass loss came from the WAIS, since they calculated that the East Antarctic Ice Sheet mass balance was  $0 \pm 56 \text{ km}^3/\text{year}$ .

What these results imply about the real world is highly dependent upon their ability to truly represent what they presume to describe; and in this regard Velicogna and Wahr say there is "geophysical contamination ... caused by signals outside Antarctica," including "continental hydrology ... and ocean mass variability." The first of these confounding factors, according to them, "is *estimated* [our italics] using monthly, global water storage fields from the Global Land Data Assimilation system," while "the ocean contamination is *estimated* [our italics] using a JPL version of the Estimating Circulation and Climate of the Ocean (ECCO) *general circulation model* [our italics]."

In addition to these problems, the two researchers note that the GRACE mass solutions "do not reveal whether a gravity variation over Antarctica is caused by a change in snow and ice on the surface, a change in atmospheric mass above Antarctica, or post-glacial rebound (PGR: the viscoelastic response of the solid Earth to glacial unloading over the last several thousand years)."

To adjust for the confounding effect of the variable atmospheric mass above Antarctica, Velicogna and Wahr utilized European Centre for Medium-Range Weather Forecasts (ECMWF) meteorological fields, but they acknowledge that "there are errors in those fields," so they "*estimate* [our italics] the secular component of those errors by finding monthly differences

between meteorological fields from ECMWF and from the National Centers for Environmental Prediction."

With respect to post-glacial rebound, Velicogna and Wahr say "there are two important sources of error in PGR estimates: the ice history and Earth's viscosity profile." To deal with this problem, they "*estimate* [our italics] the PGR contribution and its uncertainties using *two* ice history *models* [our italics]."

All of these estimates and adjustments are convoluted and complex, as well as highly dependent upon various *models*. In addition, the estimates and adjustments do not deal with miniscule effects, as Velicogna and Wahr acknowledge that "the PGR contribution is much larger than the uncorrected GRACE trend." In fact, their calculations indicate that the PGR contribution exceeds that of the signal being sought *by nearly a factor of five!!!* And they are forced to admit that "a significant ice mass trend does not appear until the PGR contribution is removed."

In light of the latter *humungous* confounding problem, Velicogna and Wahr rightly state in their concluding paragraph that "the main disadvantage of GRACE is that it is more sensitive than other techniques to PGR." In fact, considering the many other adjustments they had to make, based upon *estimations* utilizing *multiple models* and *databases with errors* that had to be *further estimated*, we are led to totally discount the significance of their final result, particularly in light of the additional fact that it did not even cover a full three-year period. *Much* more likely to be *much* more representative of the truth with respect to the WAIS's mass balance are the findings of Zwally *et al.* (2005), who determined Antarctica's contribution to mean global sea level over a recent *nine*-year period to be only 0.08 mm/year compared to the five-times-greater value of 0.4 mm/year calculated by Velcogna and Wahr.

In a contemporaneous study, van de Berg *et al.* (2006) compared results of model-simulated Antarctic *surface mass balance* (SMB) -- which they derived from a regional atmospheric climate model for the time period 1980 to 2004 that used ERA-40 fields as lateral forcings -- with "all available SMB *observations* [our italics] from Antarctica (N=1900)" in a *recalibration process* that ultimately allowed them "to construct a best estimate of contemporary Antarctic SMB," where the many real-world observations employed in this process came from the studies of Vaughan *et al.* (1999), van den Broeke *et al.* (1999), Frezzotti *et al.* (2004), Karlof *et al.* (2000), Kaspari *et al.* (2004), Magand *et al.* (2004), Oerter *et al.* (1999, 2000), Smith *et al.* (2002) and Turner *et al.* (2002), which observations were derived by a number of different measurement techniques -- including stake arrays, bomb horizons and chemical analyses of ice cores that covered time periods ranging from a few years to more than a century.

As a result of this effort, van de Berg *et al.* determined that "the SMB integrated over the grounded ice sheet ( $171 \pm 3$  mm per year) exceeds previous estimates by as much as 15%," with the largest differences between their results and those of others being "up to one meter per year higher in the coastal zones of East and West Antarctica," concluding that "support or falsification of this result can only be found in new SMB observations from poorly covered high

accumulation regions in coastal Antarctica." Consequently, until such time as pertinent new data might indicate otherwise, we have little reason to believe anything much different from what they have determined, i.e., that Antarctica's grounded ice sheet has been steadily growing for the past quarter-century.

In the very same year, Wingham *et al.* (2006) "analyzed  $1.2 \times 10^8$  European remote sensing satellite altimeter echoes to determine the changes in volume of the Antarctic ice sheet from 1992 to 2003," which survey, in their words, "covers 85% of the East Antarctic ice sheet and 51% of the West Antarctic ice sheet," which together comprise "72% of the grounded ice sheet." In doing so, they found that "overall, the data, corrected for isostatic rebound, show the ice sheet growing at  $5 \pm 1$  mm per year." To calculate the ice sheet's change in *mass*, however, "requires knowledge of the density at which the volume changes have occurred," and when the researchers' best estimates of regional differences in this parameter were used, they found that "72% of the Antarctic ice sheet is gaining  $27 \pm 29$  Gt per year, a sink of ocean mass sufficient to *lower* [their italics] global sea levels by 0.08 mm per year." This net *extraction* of water from the global ocean, according to Wingham *et al.*, occurs because "mass gains from accumulating snow, particularly on the Antarctic Peninsula and within East Antarctica, exceed the ice dynamic mass loss from West Antarctica."

Also publishing in 2006, Ramillien *et al.* derived new estimates of the mass balances of the East and West Antarctic ice sheets from GRACE data for the period July 2002 to March 2005: a loss of  $107 \pm 23$  km<sup>3</sup>/year for West Antarctica and a gain of  $67 \pm 28$  km<sup>3</sup>/year for East Antarctica, which results yielded a net ice loss for the entire continent of only 40 km<sup>3</sup>/year (which translates to a mean sea level rise of 0.11 mm/year), as opposed to the 152 km<sup>3</sup>/year ice loss calculated by Velicogna and Wahr (which translates to a nearly four times larger mean sea level rise of 0.40 mm/year). Clearly, Ramillien *et al.*'s mean sea level rise is much less ominous than the much larger value calculated by Velicogna and Wahr; and it is of the same order of magnitude as the 0.08 mm/year Antarctic-induced mean sea level rise calculated by Zwally *et al.* (2005), which was derived from elevation changes based on *nine* years of satellite *radar altimetry data* obtained from the European Remote-sensing Satellites ERS-1 and -2. Even at that, the GRACE approach is still laden with a host of potential errors, as we noted in our discussion of the Velicogna and Wahr paper, and as both they and Ramillien *et al.* readily admit. In addition, as the latter researchers note in their closing paragraph, "the GRACE data time series is still very short and these results must be considered as preliminary since we cannot exclude that the apparent trends discussed in this study only reflect interannual fluctuations."

In yet another contemporary study, Remy and Frezzotti (2006) reviewed "the results given by three different ways of estimating mass balance, first by measuring the difference between mass input and output, second by monitoring the changing geometry of the continent, and third by modeling both the dynamic and climatic evolution of the continent." In describing their findings, the two researchers state that "the East Antarctica ice sheet is nowadays more or less in balance, while the West Antarctica ice sheet exhibits some changes likely to be related to climate change and is in negative balance." In addition, they report that "the current response of the Antarctica ice sheet is dominated by the background trend due to the retreat of the

grounding line, leading to a sea-level rise of 0.4 mm/yr over the short-time scale," which they describe in terms of centuries. However, they note that "later, the precipitation increase will counterbalance this residual signal, leading to a thickening of the ice sheet and thus a decrease in sea level."

In one final study from 2006, van den Broeke *et al.* employed a regional atmospheric climate model (RACMO2), with snowdrift-related processes calculated offline, to calculate the flux of solid precipitation (Ps), surface sublimation (SU), sublimation from suspended (drifting/saltating) snow particles, horizontal snow drift transport, and surface melt (ME). In doing so, they found that "even without snowdrift-related processes, modeled (Ps-SU-ME) from RACMO2 strongly correlates with 1900 spatially weighted quality-controlled in situ SSMB *observations* [our italics]," which result they describe as "remarkable," given that the "model and observations are completely independent." Then, to deal with a remaining systematic elevation bias in the model results, they applied a set of empirical corrections (at 500-m intervals) that "largely eliminated" this final deviation from reality. And after analyzing all of the data-driven results for trends over the period 1980-2004, the four Dutch researchers report that "no trend is found in *any* [our italics] of the Antarctic SSMB components, nor in the size of ablation areas."

At long last, we finally move from 2006 to 2007, as we conclude with a brief review of the paper of Krinner *et al.* (2007), who used the LMDZ4 atmospheric general circulation model (Hourdin *et al.*, 2006) to simulate Antarctic climate for the periods 1981-2000 (to test the model's ability to adequately simulate present conditions) and 2081-2100 (to see what the future might hold for the mass balance of the Antarctic Ice Sheet and its impact on global sea level). This work revealed, first of all, that "the simulated present-day surface mass balance is skilful on continental scales," which gave them confidence that their results for the end of the 21st century would be reasonably skilful as well. Of that latter period a full century from now, they determined that "the simulated Antarctic surface mass balance increases by 32 mm water equivalent per year," which corresponds "to a sea level decrease of 1.2 mm per year by the end of the twenty-first century," which would in turn "lead to a cumulated sea level decrease of about 6 cm." This result, in their words, occurs because the simulated temperature increase "leads to an increased moisture transport towards the interior of the continent because of the higher moisture holding capacity of warmer air," where the extra moisture falls as precipitation, causing the continent's ice sheet to grow.

The results of this study -- based on sea surface boundary conditions taken from IPCC Fourth Assessment Report simulations (Dufresne *et al.*, 2005) that were carried out with the IPSL-CM4 coupled atmosphere-ocean general circulation model (Marti *et al.*, 2005), of which the LMDZ4 model is the atmospheric component -- argue strongly against climate-alarmist predictions of future catastrophic sea level rise due to mass wastage of the Antarctic Ice Sheet caused by CO<sub>2</sub>-induced global warming. In fact, they suggest just the *opposite*, i.e., that CO<sub>2</sub>-induced global warming would tend to *buffer* the world against such an outcome. And that seems to be the message of most of the other major studies of the subject as well.



Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/w/waisbalance.php>.

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#### 4.6.3.4. Sea Level

How might the West Antarctic Ice Sheet influence global sea level as a result of global warming? Here, we here review what has been learned over the past decade by scientists who specialize in this particular field of research.

In a review of what was known about the West Antarctic Ice Sheet (WAIS) that was published in *Science* back in 1998, Bindschadler analyzed its historical retreat in terms of its grounding line and ice front. This work revealed that from the time of the Last Glacial Maximum to the present, the retreat of the ice sheet's grounding line had been faster than that of its ice front, which resulted in an expanding Ross Ice Shelf; and although Bindschadler wrote that "the ice front now appears to be nearly stable," there were indications that its grounding line was retreating at a rate that suggested complete dissolution of the WAIS in another 4,000 to 7,000 years. Such a retreat was calculated to result in a sustained sea level rise of 8-13 cm per century. However, even the smallest of these rates-of-rise would require, in Bindschadler's words, "a large negative mass balance for all of West Antarctica," and there were no broad-based data that supported that scenario.

A year later, Reeh (1999) reviewed what was known about the mass balances of both the Greenland and Antarctic ice sheets, concluding that the future contribution of the Greenland and Antarctic ice sheets to global sea level depends upon their *past* climate and dynamic histories as much as it does upon *future* climate. With respect to potential climate change, in fact, Reeh determined there was a broad consensus that the effect of a 1°C climatic warming on the Antarctic ice sheet would be a *fall* in global sea level on the order of 0.2 to 0.7 millimeters per year.

The following year, Cuffey and Marshall (2000) reevaluated previous model estimates of the Greenland ice sheet's contribution to sea level rise during the last interglacial, based on a recalibration of oxygen-isotope-derived temperatures from central Greenland ice cores. Their results suggested that the Greenland ice sheet was much smaller during the last interglacial than previously thought, with melting of the ice sheet contributing somewhere between four and five and a half meters to sea level rise. According to Hvidberg (2000), this finding suggests that "high sea levels during the last interglacial should not be interpreted as evidence for extensive melting of the West Antarctic Ice Sheet, and so challenges the hypothesis that the West Antarctic is particularly sensitive to climate change."

Jumping ahead five years, Oppenheimer and Alley (2005) discussed "the degree to which warming can affect the rate of ice loss by altering the mass balance between precipitation rates on the one hand, and melting and ice discharge to the ocean through ice streams on the other," with respect to both the West Antarctic and Greenland Ice Sheets. Their review of the subject led them to conclude that we simply do not know if these ice sheets had made a significant contribution to sea level rise over the past several decades.

One year later, however, the world was exposed to a far different view of the issue, when Velicogna and Wahr (2006) used measurements of time-variable gravity from the Gravity Recovery and Climate Experiment (GRACE) satellites to determine mass variations of the Antarctic ice sheet for the 34 months between April 2002 and August 2005. When all was said and done -- which included a lot of dubious approximations -- the two researchers concluded that "the ice sheet mass decreased significantly, at a rate of  $152 \pm 80 \text{ km}^3/\text{year}$  of ice, equivalent to  $0.4 \pm 0.2 \text{ mm/year}$  of global sea level rise," all of which mass loss came from the WAIS, since they calculated that the East Antarctic Ice Sheet mass balance was  $0 \pm 56 \text{ km}^3/\text{year}$ . What these results imply about the real world is highly dependent upon their ability to truly represent what they presume to describe; and in this regard Velicogna and Wahr say there is "geophysical contamination ... caused by signals outside Antarctica," including "continental hydrology ... and ocean mass variability." The first of these confounding factors, according to them, "is *estimated* [our italics] using monthly, global water storage fields from the Global Land Data Assimilation system," while "the ocean contamination is *estimated* [our italics] using a version of the Estimating Circulation and Climate of the Ocean (ECCO) *general circulation model* [our italics]."

In addition to these problems, the two researchers note that the GRACE mass solutions "do not reveal whether a gravity variation over Antarctica is caused by a change in snow and ice on the surface, a change in atmospheric mass above Antarctica, or post-glacial rebound (PGR: the viscoelastic response of the solid Earth to glacial unloading over the last several thousand years)."

To adjust for the confounding effect of the variable atmospheric mass above Antarctica, Velicogna and Wahr utilized European Centre for Medium-Range Weather Forecasts (ECMWF) meteorological fields, but they acknowledge "there are errors in those fields," so they "*estimate*

[our italics] the secular component of those errors by finding monthly differences between meteorological fields from ECMWF and from the National Centers for Environmental Prediction."

With respect to post-glacial rebound, the two researchers say "there are two important sources of error in PGR estimates: the ice history and Earth's viscosity profile." To deal with this problem, they "*estimate* [our italics] the PGR contribution and its uncertainties using *two* ice history *models* [our italics]."

All of these estimates and adjustments are convoluted and complex, as well as highly dependent upon various *models*. In addition, the estimates and adjustments do not deal with miniscule effects, as Velicogna and Wahr acknowledge that "the PGR contribution is much larger than the uncorrected GRACE trend." In fact, their calculations indicate that the PGR contribution exceeds that of the signal being sought *by nearly a factor of five!!!* And they are forced to admit that "a significant ice mass trend does not appear until the PGR contribution is removed."

In light of the latter *humungous* confounding problem, Velicogna and Wahr rightly state in their concluding paragraph that "the main disadvantage of GRACE is that it is more sensitive than other techniques to PGR." In fact, considering the many other adjustments they had to make, based upon *estimations* utilizing *multiple models* and *databases with errors* that had to be *further estimated*, we are led to totally discount the significance of their final result, particularly in light of the additional fact that it did not even cover a full three-year period. *Much* more likely to be *much* more representative of the truth with respect to the WAIS's mass balance are the findings of Zwally *et al.* (2005), who determined Antarctica's contribution to mean global sea level over a recent *nine*-year period to be only 0.08 mm/year compared to the five-times-greater value of 0.4 mm/year calculated by Velcogna and Wahr.

Skipping ahead one more year, Ramillien *et al.* (2006) also used GRACE data to derive estimates of the mass balances of the East and West Antarctic ice sheets for the period July 2002 to March 2005, obtaining a loss of  $107 \pm 23 \text{ km}^3/\text{year}$  for West Antarctica and a gain of  $67 \pm 28 \text{ km}^3/\text{year}$  for East Antarctica, which results yielded a net ice loss for the entire continent of only  $40 \text{ km}^3/\text{year}$  (which translates to a mean sea level rise of 0.11 mm/year), as opposed to the  $152 \text{ km}^3/\text{year}$  ice loss calculated by Velicogna and Wahr (which translates to a nearly four times larger mean sea level rise of 0.40 mm/year). Clearly, Ramillien *et al.*'s mean sea level rise is much less ominous than the much larger value calculated by Velicogna and Wahr; and it is of the same order of magnitude as the 0.08 mm/year Antarctic-induced mean sea level rise calculated by Zwally *et al.* (2005), which was derived from elevation changes based on nine years of satellite radar altimetry data obtained from the European Remote-sensing Satellites ERS-1 and -2. Even at that, the GRACE approach is still laden with a host of potential errors, as we noted in our discussion of the Velicogna and Wahr paper. In addition, as Ramillien *et al.* note in their closing paragraph, "the GRACE data time series is still very short and these results must be considered as preliminary since we cannot exclude that the apparent trends discussed

in this study only reflect interannual fluctuations," which caveat also applies to the Velicogna and Wahr analysis.

About the same time, Wingham *et al.* (2006) "analyzed  $1.2 \times 10^8$  European remote sensing satellite altimeter echoes to determine the changes in volume of the Antarctic ice sheet from 1992 to 2003," which survey, in their words, "covers 85% of the East Antarctic ice sheet and 51% of the West Antarctic ice sheet," which together comprise "72% of the grounded ice sheet." In doing so, they found that "overall, the data, corrected for isostatic rebound, show the ice sheet *growing* [our italics] at  $5 \pm 1$  mm per year." To calculate the ice sheet's change in mass, however, "requires knowledge of the density at which the volume changes have occurred," and when the researchers' best estimates of regional differences in this parameter were used, they found that "72% of the Antarctic ice sheet is gaining  $27 \pm 29$  Gt per year, a sink of ocean mass sufficient to *lower* [their italics] global sea levels by 0.08 mm per year." This net *extraction* of water from the global ocean, according to Wingham *et al.*, occurs because "mass gains from accumulating snow, particularly on the Antarctic Peninsula and within East Antarctica, exceed the ice dynamic mass loss from West Antarctica."

In yet another contemporary study, Remy and Frezzotti (2006) reviewed "the results given by three different ways of estimating mass balance, first by measuring the difference between mass input and output, second by monitoring the changing geometry of the continent, and third by modeling both the dynamic and climatic evolution of the continent." In describing their findings, the two researchers state that "the East Antarctica ice sheet is nowadays more or less in balance, while the West Antarctica ice sheet exhibits some changes likely to be related to climate change and is in negative balance." In addition, they report that "the current response of the Antarctica ice sheet is dominated by the background trend due to the retreat of the grounding line, leading to a sea-level rise of 0.4 mm/yr over the short-time scale," which they describe in terms of *centuries*. However, they note that "later, the precipitation increase will counterbalance this residual signal, leading to a *thickening* of the ice sheet and thus a *decrease* in sea level [our italics]."

Last of all, we end once again with the study of Krinner *et al.* (2007), who used the LMDZ4 atmospheric general circulation model of Hourdin *et al.* (2006) to simulate Antarctic climate for the periods 1981-2000 (to test the model's ability to adequately simulate present conditions) and 2081-2100 (to see what the future might hold for the mass balance of the Antarctic Ice Sheet and its impact on global sea level). This work revealed, first of all, that "the simulated present-day surface mass balance is skilful on continental scales," which gave them confidence that their results for the end of the 21st century would be reasonably skilful as well. Of that latter period some 90 years from now, they determined that "the simulated Antarctic surface mass balance increases by 32 mm water equivalent per year," which corresponds "to a sea level *decrease* [our italics] of 1.2 mm per year by the end of the twenty-first century," which would in turn "lead to a cumulated sea level decrease of about 6 cm." This result, in their words, occurs because the simulated temperature increase "leads to an increased moisture transport towards the interior of the continent because of the higher moisture holding capacity of warmer air," where the extra moisture falls as precipitation, causing the continent's ice sheet to grow.

The results of this study -- based on sea surface boundary conditions taken from IPCC Fourth Assessment Report simulations (Dufresne *et al.*, 2005) that were carried out with the IPSL-CM4 coupled atmosphere-ocean general circulation model (Marti *et al.*, 2005), of which the LMDZ4 model is the atmospheric component -- argue strongly against climate-alarmist predictions of future catastrophic sea level rise due to mass wastage of the Antarctic Ice Sheet caused by CO<sub>2</sub>-induced global warming. In fact, they suggest just the *opposite*, i.e., that CO<sub>2</sub>-induced global warming would tend to *buffer* the world against such an outcome.

All in all, it would appear there has been very little change in global sea level due to wastage of the WAIS over the past few decades, and that there will probably be little change in both the near and far future. In fact, what wastage might occur along the coastal area of the ice sheet over the long term would likely be countered, or even *more* than countered, by greater inland snowfall. And in the case of the latter possibility, or *probability*, the entire Antarctic Ice Sheet could well compensate for any long-term wastage of the Greenland Ice Sheet that might occur, in terms of how these phenomena impact global sea level.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/w/waissealevel.php>.

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#### **4.7. Sea Level Rise**

Periodically, individual scientists and groups of scientists analyze global sets of sea level data to see if there is any indication of a dramatic increase in the mean rate-of-rise of the global ocean surface in response to the supposedly unprecedented warming of the planet over the course of the 20th century, which climate alarmists claim should be accelerating sea level rise and leading to catastrophic coastal flooding around the world. What follows, then, is a brief summary of such findings as they have appeared in the peer-reviewed scientific literature over the past few years.

Cazenave *et al.* (2003) studied climate-related processes that cause variations in mean global sea level on interannual to decadal time scales, focusing on thermal expansion of the oceans and continental water mass balance. In doing so, they determined that the rate of thermal-induced sea level rise over the past 40 years was about 0.5 mm/year. From early 1993 to the end of the 20th century, however, analyses of TOPEX-Poseidon altimetry data and the global ocean temperature data of Levitus *et al.* (2000) yielded rates-of-rise that were approximately *six times greater* than the mean four-decade rate, which suggested to them that "an acceleration took place in the recent past, likely related to warming of the world ocean." However, as they alternatively note, "the recent rise may just correspond to the rising branch of a decadal oscillation." In addition, they say that "satellite altimetry and *in situ* temperature data have their own uncertainties and it is still difficult to affirm with certainty that sea level rise is indeed accelerating." In fact, they cite the work of Nerem and Mitchum (2001) as indicating that "about 20 years of satellite altimetry data would be necessary to detect, with these data alone, any acceleration in sea level rise."



Mörner (2004) provided a more expansive setting for his analysis of the subject by noting that “prior to 5000-6000 years before present, all sea level curves are dominated by a general rise in sea level in true glacial eustatic response to the melting of continental ice caps,” but that “sea level records are now dominated by the irregular redistribution of water masses over the globe ... primarily driven by variations in ocean current intensity and in the atmospheric circulation system and maybe even in some deformation of the gravitational potential surface.” With respect to the last 150 years, he reports that “the mean eustatic rise in sea level for the period 1850-1930 was [on] the order of 1.0-1.1 mm/year,” but that “after 1930-40, this rise seems to have stopped (Pirazzoli *et al.*, 1989; Mörner, 1973, 2000).” This stasis, in his words, “lasted, at least, up to the mid-60s.” Thereafter, with the advent of the TOPEX/Poseidon mission, Mörner notes that “the record can be divided into three parts: (1) 1993-1996 with a clear trend of stability, (2) 1997-1998 with a high-amplitude rise and fall recording the ENSO event of these years and (3) 1998-2000 with an irregular record of no clear tendency.” Most important of all, in his words, Mörner states “there is a total absence of any recent ‘acceleration in sea level rise’ as often claimed by IPCC and related groups,” and, therefore, “there is no fear of any massive future flooding as claimed in most global warming scenarios.”

Church *et al.* (2004) used TOPEX/Poseidon satellite altimeter data to estimate global empirical orthogonal functions, which they combined with historical tide gauge data, to estimate monthly distributions of large-scale sea level variability and change over the period 1950-2000. Their resultant “best estimate” of the rate of globally-averaged sea level rise over the last half of the 20th century was  $1.8 \pm 0.3$  mm/year. In addition, they noted that “decadal variability in sea level is observed, but to date there is no detectable secular increase in the rate of sea level rise over the period 1950-2000.” What is more, they reported that no increase in the rate of sea level rise has been detected for the *entire* 20th century, citing the work of Woodworth (1990) and Douglas (1992).

Cazenave and Nerem (2004) summarized what was known shortly after the turn of the century about past and then-current rates of sea level rise *because*, in their words, “determining the rate of sea level change over the last century is critically important in order to determine if the present-day rate of sea level change has changed appreciably,” which, as we have noted, is something one would expect to have occurred if 20th-century global warming was truly as unprecedented as climate alarmists say it was, bringing the planet to a level of warmth they claim was unprecedented over the past two millennia and within less than a degree of the all-time high temperature of the last *million* or more years. What they learned in this endeavor was that “the geocentric rate of global mean sea level rise over the last decade (1993-2003) is now known to be very accurate,  $+2.8 \pm 0.4$  mm/year, as determined from TOPEX/Poseidon and Jason altimeter measurements,” and that “this rate is significantly larger than the historical rate of sea level change measured by tide gauges during the past decades (in the range of 1-2 mm/year).”

*However*, as Cazenave and Nerem continue, “the altimetric rate could still be influenced by decadal variations of sea level unrelated to long-term climate change, such as the Pacific Decadal Oscillation, and thus a longer time series is needed to rule this out.” They also noted

that satellite altimetry had revealed a “non-uniform geographical distribution of sea level change, with some regions exhibiting trends about 10 times the global mean.” In addition, they note that “for the past 50 years, sea level trends caused by change in ocean heat storage also show high regional variability,” which fact “has led to questions about whether the rate of 20th-century sea level rise, based on poorly distributed historical tide gauges, is really representative of the true global mean.” Consequently, and in spite of the many new instruments and techniques that are being used to search for a global warming signal in global sea level data, Cazenave and Nerem report that “these tools seem to have raised more questions than they have answered.”

Noting that global climate *models* “show an increase in the rate of global average sea level rise during the 20th century,” but that several prior studies (Douglas, 1991, 1992; Maul and Martin, 1993; Church *et al.*, 2004; Holgate and Woodworth, 2004) had shown the *measured* rate of global sea level rise to have been rather stable over the past hundred years, White *et al.* (2005) conducted yet another analysis of the available data in an attempt to find the elusive predicted increase in the global sea level’s rate of rise, comparing estimates of coastal and global averaged sea level for 1950 to 2000. When all was said and done, their results confirmed the earlier findings of “no significant increase in the rate of sea level rise during this 51-year period,” i.e., over the last half of the 20th century, including its last two decades, which are especially demonized by climate alarmists for their supposedly unprecedented rate of temperature increase.

Lombard *et al.* (2005) investigated the *thermosteric* or temperature-induced sea-level change of the last 50 years using the global ocean temperature data of Levitus *et al.* (2000) and Ishii *et al.* (2003). This work revealed that thermosteric sea level variations are dominated by decadal oscillations of the planet’s chief ocean-atmosphere climatic perturbations (El Niño-Southern Oscillation, Pacific Decadal Oscillation and North Atlantic Oscillation); and in terms of the global mean, as they describe it, thermosteric trends computed over 10-year windows “show large fluctuations in time, with positive values (in the range 1 to 1.5 mm/year for the decade centered on 1970) and negative values (-1 to -1.5 mm/year for the decade centered on 1980).” In the mean, however, and over the full half-century period Lombard *et al.* investigated, there was a net rise in sea level due to the thermal expansion of sea water, *but only because the record began at the bottom of a trough and ended at the top of a peak*. In between these two points, there were both higher and lower values, so that one cannot be sure what would be implied if earlier data were available or what will be implied as more data are acquired. Noting that sea level trends derived from TOPEX/Poseidon altimetry over 1993-2003 are “mainly caused by thermal expansion” and are thus “very likely a non-permanent feature,” Lombard *et al.* thus concluded that “we simply cannot extrapolate sea level into the past or the future using satellite altimetry alone.” Consequently, even the 50 years of global ocean temperature data we possess are insufficient to tell us much about the degree of global warming that may have occurred over the past half-century, as any long-term increase in global sea level that may have been caused by the temperature increase is absolutely *dwarfed* by decadal-scale variability.

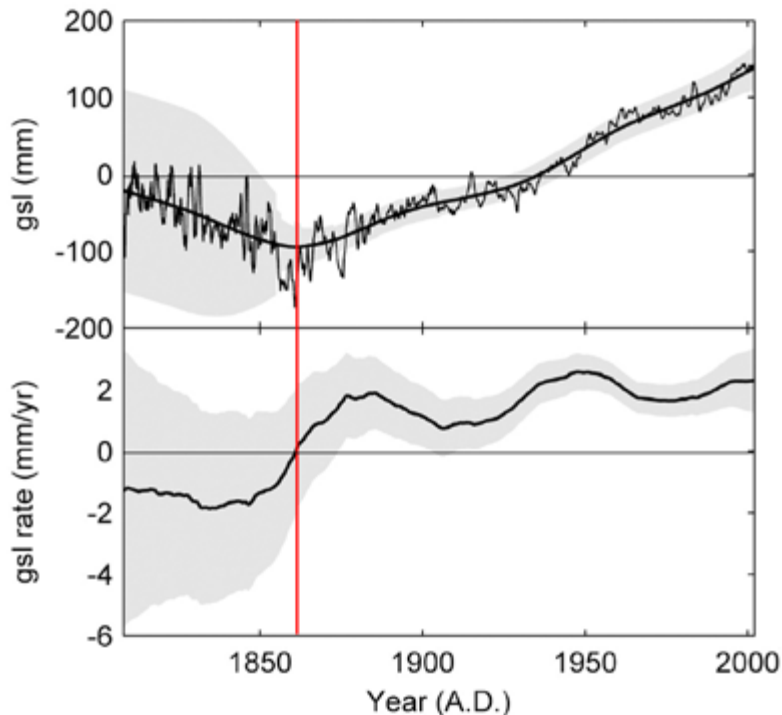
Carton *et al.* (2005) introduced their study of the subject by noting that “recent altimeter observations indicate an increase in the rate of sea level rise during the past decade to 3.2 mm/year, well above the centennial estimate of 1.5-2 mm/year,” noting further that “this apparent increase could have resulted from enhanced melting of continental ice,” as climate alarmists often claim, “or from decadal changes in thermosteric and halosteric effects.” Hence, they explored these opposing options “using the new eddy-permitting Simple Ocean Data Assimilation version 1.2 reanalysis of global temperature, salinity, and sea level spanning the period 1968-2001,” and in doing so they determined that “the effect on global sea level rise of changing salinity is small except in subpolar regions.” However, they found that warming-induced steric effects “are enough to explain much of the observed rate of increase in the rate of sea level rise in the last decade of the 20th century without need to invoke acceleration of melting of continental ice.” And as determined by Lombard *et al.*, as described in the preceding paragraph, the high thermosteric-induced rate-of-rise of global sea level over the past decade is likely “a non-permanent feature” of the global ocean’s transient thermal behavior. Consequently, and in harmony with the findings of Levitus *et al.* (2005) and Volkov and van Aken (2005), Carton *et al.* found no need to invoke the melting of land-based glacial ice to explain the observed increase in global sea-level rise of the past decade.

Even more revealing was the globally-distributed sea level time series study of Jevrejeva *et al.* (2006), who analyzed information contained in the *Permanent Service for Mean Sea Level* database using a method based on Monte Carlo Singular Spectrum Analysis and removed 2- to 30-year quasi-periodic oscillations to derive nonlinear long-term trends for 12 large ocean regions, which they combined to produce the mean global sea level (gsl) and gsl rate-of-rise (gsl rate) curves depicted in the figure on the next page.

In discussing their findings, Jevrejeva *et al.* say they show that “global sea level rise is irregular and varies greatly over time,” noting that “it is apparent that rates in the 1920-1945 period are likely to be as large as today’s.” In addition, they report that their “global sea level trend estimate of  $2.4 \pm 1.0$  mm/year for the period from 1993 to 2000 matches the  $2.6 \pm 0.7$  mm/year sea level rise found from TOPEX/Poseidon altimeter data.” With respect to what the four researchers describe as “the discussion on whether sea level rise is accelerating,” therefore, their results pretty much answer the question in the negative.

The observations described above make us wonder why late 20th-century global warming - which climate alarmists describe as having been *unprecedented over the past two millennia* - cannot be detected in global sea level data. We are even more intrigued about the matter in light of the fact that the effects of the warming that led to the demise of the Little Ice Age - which by climate-alarmist contention should have been considerably less dramatic than the warming of the late 20th century - are *readily* apparent to the right of the vertical red line in the above figure. Likewise, we are perplexed by the demonstrable *fact* that although the rising atmospheric CO<sub>2</sub> concentration - which climate alarmists claim is primarily responsible for the supposedly unprecedented global warming of the late 20th century - experienced a dramatic increase in its rate-of-rise just after 1950 (shifting from a 1900-1950 mean rate-of-rise of 0.33 ppm/year to a 1950-2000 mean rate-of-rise of 1.17 ppm/year), the mean global sea level rate-

of-rise did not trend upwards after 1950, nor has it subsequently exceeded its 1950 rate-of-rise. These observations clearly indicate that something is drastically wrong with the warped world-view of the world's climate alarmists.



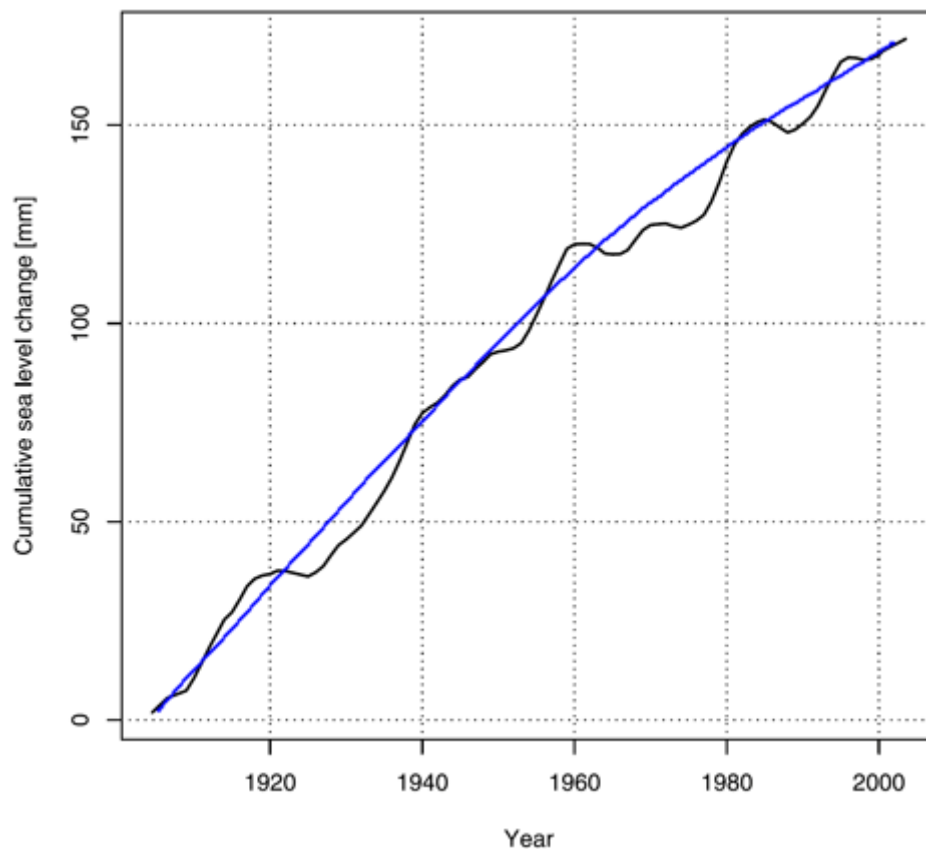
**Mean global sea level (top), with shaded 95% confidence interval, and mean gsl rate-of-rise (bottom), with shaded standard error interval, adapted from Jevrejeva *et al.* (2006).**

In concluding our examination of the peer-reviewed sea level science, we report the findings of the most recent study of Holgate (2007). In a previous paper, Holgate and Woodworth (2004) derived a mean global sea level history from 177 coastal tide gauge records that spanned the period 1955-1998; and in an attempt to extend that record back in time another half-century, Holgate chose nine much longer high-quality records from around the world (New York, Key West, San Diego, Balboa, Honolulu, Cascais, Newlyn, Trieste and Auckland) to see if their combined mean progression over the 1955-1998 period was similar enough to the concomitant mean sea level history of the 177 stations to employ the mean nine-station record as a reasonable representation of mean global sea level history for the much longer period stretching from 1904 to 2003.

In comparing the sea level histories derived from the two data sets, Holgate found that their mean rates-of-rise were indeed similar over the second half of the 20th century; and this observation thus implied, in Holgate's words, that "a few high quality records from around the world can be used to examine large spatial-scale decadal variability as well as many gauges from each region are able to [do]."

As a result of this finding, Holgate constructed the nine-station-derived wavering black line in the figure below as a reasonable best representation of the 1904-2003 mean global sea level history of the world, and based on that history calculated that the mean rate of global sea level rise was “larger in the early part of the last century ( $2.03 \pm 0.35$  mm/year 1904-1953), in comparison with the latter part ( $1.45 \pm 0.34$  mm/year 1954-2003).”

Another way of thinking about the century-long sea level history portrayed in the figure below is suggested by the blue curve we have fit to it, which indicates that mean global sea level may have been rising, in the mean, ever more slowly with the passage of time throughout the entire last hundred years, with a possible acceleration of that trend over the last few decades.



**Cumulative increase in mean global sea level (1904-2003) derived from nine high-quality tide gauge records from around the world. Adapted from Holgate (2007).**

In any event, and whichever way one looks at the findings of Holgate - either as two successive linear trends (representative of the mean rates-of-rise of the first and last halves of the 20th century) or as one longer continuous curve (such as we have drawn) - the nine select tide gauge

records indicate that the mean rate of global sea level rise has *not* accelerated over the recent past (if anything, in fact, it's done just the *opposite*), when Mr. Gore and the climate alarmists have incessantly *claimed* that (1) the earth warmed to a degree that is unprecedented over many millennia, (2) the warming resulted in a net accelerated melting of the vast majority of the world's mountain glaciers and polar ice caps, and (3) global sea level rose at an ever increasing rate. The real-world data-based results of Holgate, as well as those of all of the other studies noted in this brief examination, clearly suggest that *all of these claims appear to be false*.

Additional information on this topic, including reviews on sea level not discussed here, can be found at [http://www.co2science.org/subject/s/subject\\_s.php](http://www.co2science.org/subject/s/subject_s.php) under the heading Sea Level.

#### **4.8. Medieval Warm Period**

Additional information on this topic, including reviews on the Medieval Warm Period not discussed here, can be found at [http://www.co2science.org/subject/m/subject\\_m.php](http://www.co2science.org/subject/m/subject_m.php) under the heading Medieval Warm Period.

##### **4.8.1. Overview**

It is frequently *claimed* that temperatures over the latter part of the 20th century were higher than those experienced at any other time over the past one to two millennia, based primarily on the work of Mann *et al.* (1998, 1999) and Mann and Jones (2003). Their reason for doing so is to use this *claim* to support the related *claim* that anthropogenic CO<sub>2</sub> emissions from the burning of fossil fuels have caused dramatic global warming, which if allowed to continue will produce a number of catastrophic consequences. However, one can disprove the first of these claims, so as to remove support for the second, by demonstrating that about 1000 years ago, when there was approximately 25% *less* CO<sub>2</sub> in the atmosphere than there is currently, temperatures throughout the entire world were equally as high as (or even *higher* than) they were over the latter part of the 20th century – and such a project has actually been conducted. This real-world data-based *fact*, as evidenced in the material below, conclusively demonstrates there is nothing unnatural about the planet's current level of warmth, and that it is likely caused by the recurrence of whatever cyclical phenomenon created the equal or even *greater* warmth of the Medieval Warm Period (MWP).

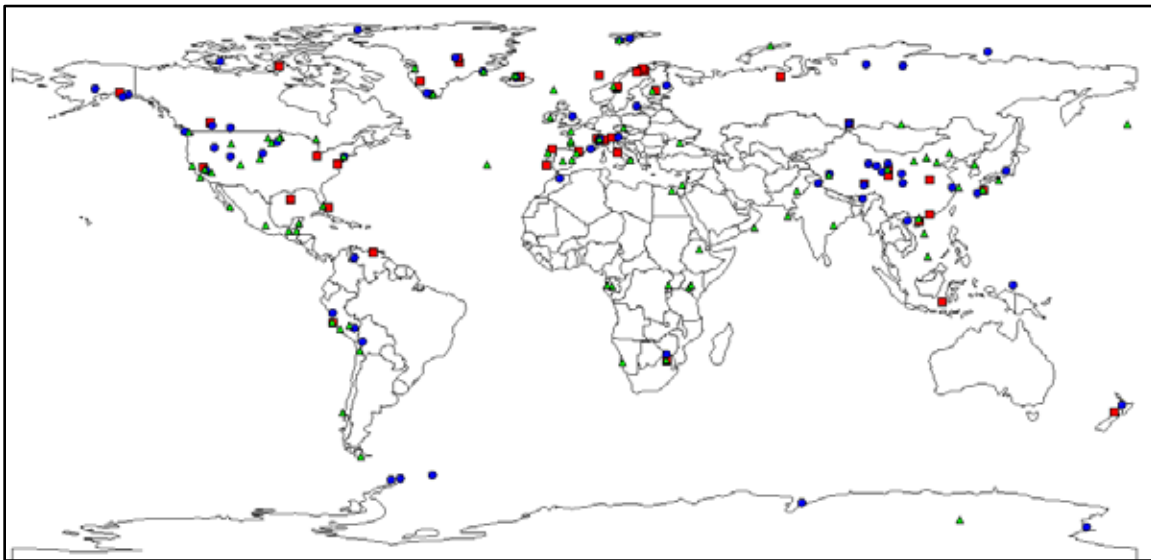
##### **4.8.1.1. Was There a Global MWP?**

The degree of warming and climatic influence during the MWP varied from region to region and, hence, its consequences were manifested in a number of different ways. But that it occurred and was a global phenomenon is certain; and there are literally hundreds of peer-reviewed scientific articles that bear witness to this truth.

In likely the largest synthesis of MWP research articles in the world, *CO<sub>2</sub> Science* (<http://www.co2science.org/data/mwp/mwpp.php>) has highlighted a different MWP study each week on its website for the past couple of years, documenting the global nature of this warm-

temperature era. To date, they have analyzed approximately 200 research papers, demonstrating the reality of this natural climatic fluctuation.

Figure 1 below illustrates the spatial distribution of the proxy climate studies analyzed by *CO<sub>2</sub> Science* according to three different categories. The first of these categories, denoted by the red squares, is comprised of studies where *the scientists who conducted the work* provided *quantitative* data that enable one to determine the degree by which the peak temperature of the MWP differed from the peak temperature of the Current Warm Period (CWP). The second category is comprised of studies where *the scientists who conducted the work* provided *qualitative* data that enable one to determine which of the two periods was warmer, but not by how much (blue circles). The third category is comprised of studies where the MWP was evident in the study's data, but where the data did not provide a means by which the warmth of the MWP could be compared with that of the CWP (green triangles). This third category may seem rather innocuous, but such studies contradict the climate-alarmist claim that the MWP, if it occurred at all, was only a *regional* phenomenon experienced by lands significantly influenced by the North Atlantic Ocean. This category also includes studies that are based on data related to parameters other than temperature, such as precipitation. These studies are helpful to define the *timeframe* of the MWP; but they are not employed to infer anything about either its quantitative or qualitative thermal strength. As can be seen from the figure, evidence of the MWP has been uncovered at locations throughout the world, revealing the truly global nature of this phenomenon.



**Figure 1.** Plot of the locations of proxy climate studies for which (a) quantitative determinations of the temperature difference between the MWP and CWP can be made (red squares), (b) qualitative determinations of the temperature difference between the MWP and CWP can be made (blue circles), and (c) neither quantitative nor qualitative determinations can be made, with the studies simply indicating that the Medieval Warm Period did indeed occur in the studied region (green triangles).

#### 4.8.1.2. *When Did the MWP Occur and Was it Warmer Than the CWP?*

A second question often posed with respect to the MWP is: *when did it occur?* A basic histogram of the *timeframe* (start year to end year) associated with the MWP of all studies plotted in Figure 1 is shown in Figure 2. As indicated in the figure, the peak timeframe of all studies occurs around 1050 AD, within a more generalized 800 to 1300 AD warm era.

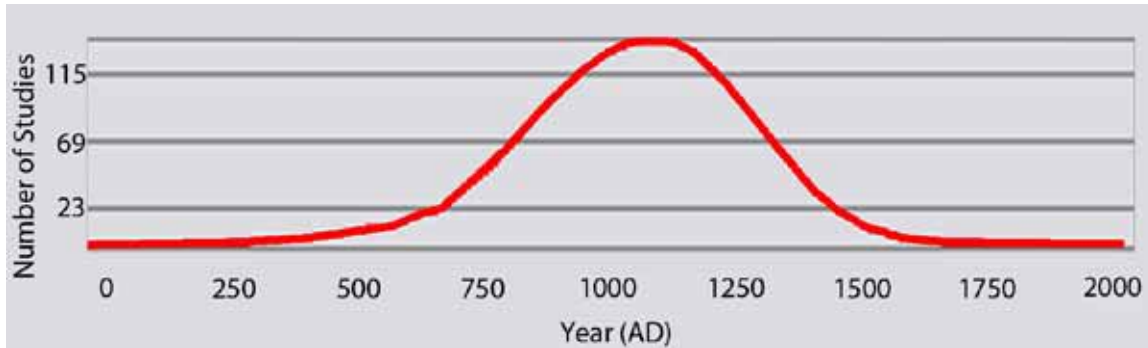


Figure 2. Histogram showing the timeframe associated with all MWP studies plotted in Figure 1.

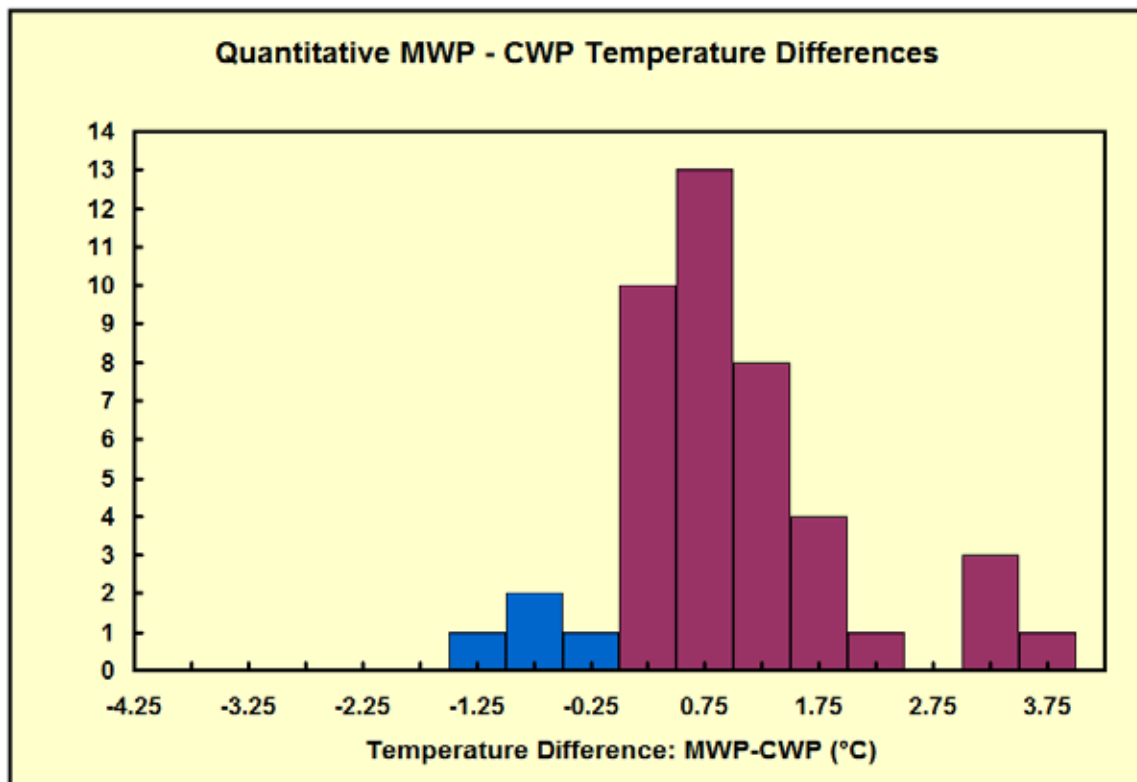
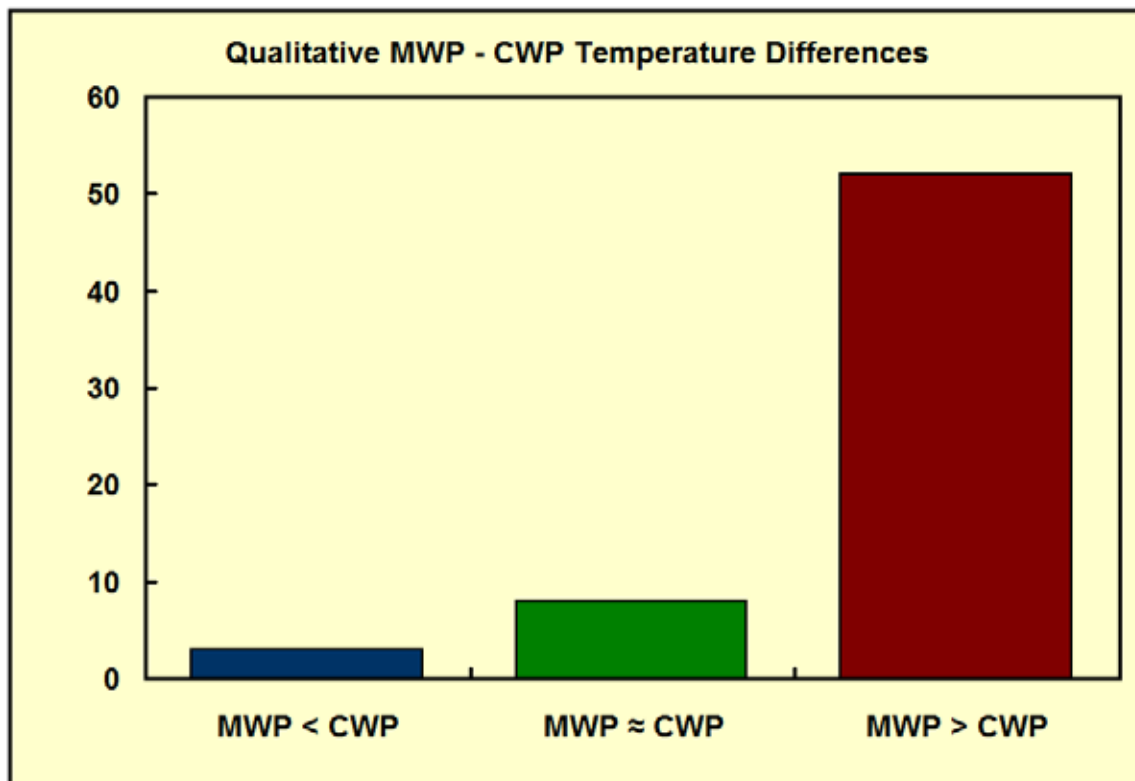


Figure 3. The distribution, in 0.5°C increments, of studies that allow one to identify the degree by which peak Medieval Warm Period temperatures either exceeded (positive values, red) or fell short of (negative values, blue) peak Current Warm Period temperatures.



With respect to how warm it was during this period, we have plotted the frequency distribution of all *MWP-CWP temperature differentials* from all quantitative studies (red squares) shown in Figure 1 to create Figure 3. As this figure reveals, there are a few studies in which the MWP was determined to have been cooler than the CWP (blue columns); but the vast majority of the temperature differentials are positive (red columns), indicating the MWP was warmer than the CWP. The average of all such differentials is 1.06°C, while the median is 0.95°C.

We can further generalize the superior warmth of the MWP by analyzing the *qualitative* studies in Figure 1, which we have done in Figure 4. Here we have plotted the number of studies in Figure 1 in which the MWP was warmer than, cooler than, or about the same as, the CWP, based upon actual data presented by the authors of the original works. As with Figure 3, there are a couple of studies in which the MWP was determined to have been cooler than the CWP, plus a few that found them of approximately the same warmth; but the vast majority of studies indicates an MWP that was *warmer* than the CWP.



**Figure 4.** The distribution of studies that allow one to determine whether peak Medieval Warm Period temperatures were warmer than (red), equivalent to (green), or cooler than (blue), peak Current Warm Period temperatures.

The huge – and still growing! – Medieval Warm Period Project of *CO<sub>2</sub> Science* hosts a readily-accessible collection of totally independent databases that demonstrate a globally-synchronous

MWP between approximately 800 and 1300 AD, when temperatures were significantly warmer than those of the present. The strength of this thesis is enhanced by the fact that the work cited above derives from over 200 peer-reviewed journal articles produced by over 630 individual scientists working in 370 separate institutions from 39 different countries – and counting, as *CO<sub>2</sub> Science* has many additional articles “waiting in the wings” to be reviewed. If there were ever an example of true scientific consensus on an issue, this should be it. Nevertheless, climate alarmists continue to ignore -- and even deny -- the reality and implications of this important natural warm period of earth’s climatic history

As indicated in the beginning of this section, it is often *claimed* that temperatures over the latter part of the 20th century were higher than those experienced at any other time over the past one to two millennia. Based upon the synthesis of real-world data presented here (and hereafter), however, that claim is seen to be false. Thus, the corollary claim that anthropogenic CO<sub>2</sub> emissions from the burning of fossil fuels have caused the planet’s current “unprecedented” warmth cannot be substantiated; for late 20<sup>th</sup>-century temperatures are *not* unprecedented, falling well within the range of natural millennial-scale variability. Consequently, there is no compelling reason to believe the historical rise in the atmosphere’s CO<sub>2</sub> concentration had any significant impact on 20<sup>th</sup> century temperatures, since it was warmer than it is now fully 1000 years ago, when there was 25% less CO<sub>2</sub> in the air than there is today.

In the rest of this section, we further demonstrate the truth of this thesis by highlighting the results of several studies from regions across the globe that show the existence of a Medieval Warm Period.

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### 4.8.2. Africa

Based on the temperature and water needs of the crops that were cultivated by the first agropastoralists of southern Africa, Huffman (1996) constructed a climate history of the region based on archaeological evidence acquired from various Iron Age settlements. In the course of completing this project, dated relic evidence of the presence of cultivated sorghum and millets was considered by Huffman to be so strong as to essentially *prove* that the climate of the subcontinent-wide region must have been *warmer and wetter than it is today* from

approximately AD 900-1300, for these crops cannot be grown in this part of southern Africa under current climatic conditions, which are much too cool and dry.

Other evidence for this conclusion comes from Tyson *et al.* (2000), who obtained a quasi-decadal record of oxygen and carbon-stable isotope data from a well-dated stalagmite of Cold Air Cave in the Makapansgat Valley (30 km southwest of Pietersburg, South Africa), which they augmented with 5-year-resolution temperature data that they reconstructed from color variations in banded growth-layer laminations of the stalagmite that were derived from a relationship calibrated against actual air temperatures obtained from a surrounding 49-station climatological network over the period 1981-1995, which had a correlation of +0.78 that was significant at the 99% confidence level. This record revealed the existence of a significantly warmer-than-present period that began prior to AD 1000 and lasted to about AD 1300. In fact, Tyson *et al.* report that the "maximum warming at Makapansgat at around 1250 produced conditions up to 3-4°C hotter than those of the present."

In a similar study, Holmgren *et al.* (2001) derived a 3000-year temperature record for South Africa that revealed several multi-century warm and cold periods. Of particular interest with respect to the Medieval Warm Period was their finding of a dramatic warming at approximately AD 900, when temperatures reached a level that was 2.5°C higher than that prevailing at the time of their analysis of the data.

Lamb *et al.* (2003) provided strong evidence for the hydrologic fingerprint of the Medieval Warm Period in Central Kenya via a study of pollen data obtained from a sediment core taken from Crescent Island Crater, which is a sub-basin of Lake Naivasha. Of particular interest in this regard is the strong similarity between their results and those of Verschuren *et al.* (2000). The most striking of these correspondences occurred over the period AD 980 to 1200, when lake-level was at an 1100-year low and woody taxa were significantly underrepresented in the pollen assemblage. We also note, with respect to this finding, that when two independent data sets tell essentially the same story -- in this particular case, a tale of a two-century-long depression of precipitation and elevated temperature (which leads to lower lake levels) -- one can have increased confidence that the story they tell is true.

Expanding on the earlier work of Holmgren *et al.* (2001), Holmgren *et al.* (2003) developed a 25,000-year temperature history from a stalagmite retrieved from Makapansgat Valley's Cold Air Cave based on  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  measurements dated by  $^{14}\text{C}$  and high-precision thermal ionization mass spectrometry using the  $^{230}\text{Th}/^{234}\text{U}$  method. This work revealed, in the words of the nine researchers [together with our interspersed notes], that "cooling is evident from ~6 to 2.5ka [thousand years before present, during the long interval of coolness that preceded the Roman Warm Period], followed by warming between 1.5 and 2.5 ka [the Roman Warm Period] and briefly at ~AD 1200 [the Medieval Warm Period, which followed the Dark Ages Cold Period]," after which "maximum Holocene cooling occurred at AD 1700 [the depth of the Little Ice Age]." They also note that "the Little Ice Age covered the four centuries between AD 1500 and 1800 and at its maximum at AD 1700 represents the most pronounced negative  $\delta^{18}\text{O}$  deviation in the entire record."

This new temperature record from far below the equator (24°S) reveals the existence of all of the major millennial-scale oscillations of climate that are evident in data collected from regions surrounding the North Atlantic Ocean. Hence, it attests to the global extent of these significant intervals of relative warmth and coolness; and it suggests that *after the coldest such period of the entire Holocene*, it was only to be expected that there would be a significant increase in mean global air temperature when the next scheduled warming occurred.

Two years later, Kondrashov *et al.* (2005) applied advanced spectral methods to fill data gaps and locate interannual and interdecadal periodicities in historical records of *annual* low- and high-water levels on the Nile River over the 1300-year period AD 622-1922. In doing so, several statistically significant periodicities were noted, including cycles at 256, 64, 19, 12, 7, 4.2 and 2.2 years. With respect to the *causes* of these cycles, the three researchers say that the 4.2- and 2.2-year oscillations are likely due to El Niño-Southern Oscillation variations, that the 7-year cycle may be related to North Atlantic influences, and that the longer-period oscillations could be due to astronomical forcings. They also note that the annual-scale resolution of their results provides a "sharper and more reliable determination of climatic-regime transitions" in tropical east Africa, including the documentation of fairly abrupt shifts in river flow at the beginning and end of the Medieval Warm Period.

Skipping forward two more years, Ngomanda *et al.* (2007) derived high-resolution (<40 years) paleoenvironmental reconstructions for the last 1500 years based on pollen and carbon isotope data obtained from sediment cores retrieved from Lakes Kamalete and Nguene in the lowland rainforest of Gabon. As for what they found, the nine researchers state that after a sharp rise at ~1200 cal yr BP, "A/H [aquatic/hygrophytic] pollen ratios showed intermediate values and varied strongly from 1150 to 870 cal yr BP, suggesting decadal-scale fluctuations in the water balance during the 'Medieval Warm Period'." Thereafter, lower A/H pollen ratios "characterized the interval from ~500 to 300 cal yr BP, indicating lower water levels during the 'Little Ice Age'." In addition, they report that "all inferred lake-level low stands, notably between 500 and 300 cal yr BP, are associated with decreases in the score of the TRFO [Tropical Rainforest] biome."

In discussing their findings, Ngomanda *et al.* state that "the positive co-variation between lake level and rainforest cover changes may indicate a direct vegetational response to regional precipitation variability," noting that, "evergreen rainforest expansion occurs during wet intervals, with contraction during periods of drought." Hence, it would appear that in this part of Western Equatorial Africa, the Little Ice Age was a time of low precipitation, low lake levels, and low evergreen rainforest presence, while much the opposite was the case during the Medieval Warm Period, when fluctuating wet-dry conditions led to fluctuating lake levels and a greater evergreen rainforest presence.

Placing these findings within a broader temporal context, Ngomanda *et al.* additionally note that "rainforest environments during the late Holocene in western equatorial Africa are characterized by successive *millennial-scale changes* [our italics] according to pollen (Elenga *et al.*, 1994, 1996; Reynaud-Farrera *et al.*, 1996; Maley and Brenac, 1998; Vincens *et al.*, 1998),

diatom (Nguetsop *et al.*, 2004), geochemical (Delegue *et al.*, 2001; Giresse *et al.*, 1994) and sedimentological data (Giresse *et al.*, 2005; Wirmann *et al.*, 2001)," and that "these changes were essentially driven by *natural* [our italics] climatic variability (Vincens *et al.*, 1999; Elenga *et al.*, 2004)," all of which observations suggest there is nothing unusual, unnatural or unprecedented about the African continent's Current Warm Period status.

Last of all, we come to the paper of Esper *et al.* (2007), who used *Cedrus atlantica* ring-width data "to reconstruct long-term changes in the Palmer Drought Severity Index (PDSI) over the past 953 years in Morocco, Northwest Africa." This work revealed, as they describe it, that "the long-term PDSI reconstruction indicates generally drier conditions before ~1350, a transition period until ~1450, and generally wetter conditions until the 1970s," after which there were "dry conditions since the 1980s." In addition, they determined that "the driest 20-year period reconstructed is 1237-1256 (PDSI = -4.2)," adding that "1981-2000 conditions are in line with this historical extreme (-3.9)." Also of significance, the six researchers note that "millennium-long temperature reconstructions from Europe (Buntgen *et al.*, 2006) and the Northern Hemisphere (Esper *et al.*, 2002) indicate that Moroccan drought changes are broadly coherent with well-documented temperature fluctuations including warmth during medieval times, cold in the Little Ice Age, and recent anthropogenic warming," which latter coherency would tend to suggest that the peak warmth of the Medieval Warm Period was *at least as great* as that of the last two decades of the 20th century *throughout the entire Northern Hemisphere*; and, if the coherency is strictly interpreted, it suggests that the warmth of the MWP was likely even *greater* than that of the late 20th century.

In light of these several research findings, which have been published in the standard peer-reviewed scientific literature, it would appear that (1) the Medieval Warm Period did indeed leave its mark over wide reaches of Africa, and that (2) the Medieval Warm Period was probably much more extreme in this part of the world than has been the Current Warm Period to this point in time.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/a/africamwp.php>.

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#### 4.8.3. Antarctica

We begin with the study of Hemer and Harris (2003), who extracted a sediment core from beneath the Amery Ice Shelf, East Antarctica, at a point that is currently about 80 km landward of the location of its present edge. In analyzing the core's characteristics over the past 5700 <sup>14</sup>C years, the two scientists observed a peak in absolute diatom abundance in general, and the abundance of *Fragilariopsis curta* in particular -- which parameters, in their words, "are associated with increased proximity to an area of primary production, such as the sea-ice zone" -- at about 750 <sup>14</sup>C yr B.P., which puts the time of *maximum Ice Shelf retreat* in close proximity to the historical time frame of the Medieval Warm Period.

Khim *et al.* (2002) likewise analyzed a number of properties of a sediment core removed from the eastern Bransfield Basin just off the northern tip of the Antarctic Peninsula, including grain size, total organic carbon content, magnetic susceptibility, biogenic silica content,  $^{210}\text{Pb}$  geochronology and radiocarbon ( $^{14}\text{C}$ ) age, all of which data clearly depicted, in their words, the presence of the "Little Ice Age and Medieval Warm period, together with preceding climatic events of similar intensity and duration," demonstrating that the same millennial-scale climatic oscillation that reverberates throughout the region of the North Atlantic is also manifest in the Southern Ocean.

At about the same time, Hall and Denton (2002) mapped the distribution and elevation of surficial deposits along the southern Scott Coast of Antarctica in the vicinity of the Wilson Piedmont Glacier, which runs parallel to the coast of the western Ross Sea from McMurdo Sound north to Granite Harbor. The chronology of the raised beaches they studied was determined from more than 60  $^{14}\text{C}$  dates of incorporated organic materials they had previously collected from hand-dug excavations (Hall and Denton, 1999); and the record the dates helped define demonstrated that near the end of the Medieval Warm Period, "as late as 890  $^{14}\text{C}$  yr BP," as Hall and Denton describe it, "the Wilson Piedmont Glacier was still *less extensive than it is now* [our italics]," demonstrating that the climate of that period was in all likelihood considerably warmer than it is currently.

Noon *et al.* (2003) used oxygen isotopes preserved in authigenic carbonate retrieved from freshwater sediments of Sombre Lake on Signy Island (60°43'S, 45°38'W) in the Southern Ocean to construct a 7000-year history of that region's climate. This work revealed that the general trend of temperature at the study site has been downward. Of most interest to us, however, is the millennial-scale oscillation of climate that is apparent in much of the record. This climate cycle is such that approximately 2000 years ago, after a thousand-year gap in the data, Signy Island experienced the relative warmth of the last vestiges of the Roman Warm Period, as delineated by McDermott *et al.* (2001) on the basis of a high-resolution speleothem  $\delta^{18}\text{O}$  record from southwest Ireland. Then comes the Dark Ages Cold period, which is also contemporaneous with what McDermott *et al.* observe in the Northern Hemisphere, after which the Medieval Warm Period appears at the same point in time and persists for the same length of time that it does in the vicinity of Ireland, whereupon the Little Ice Age sets in just as it does in the Northern Hemisphere. Finally, there is an indication of late 20th-century warming, but with still a long way to go before conditions comparable to those of the Medieval Warm Period are achieved.

Two years later, Castellano *et al.* (2005) derived a detailed history of Holocene volcanism from the sulfate record of the first 360 meters of the Dome Concordia ice core that covered the period 0-11.5 kyr BP, after which they compared their results for the past millennium with similar results obtained from eight other Antarctic ice cores. Before doing so, however, they normalized the results at each site by dividing its several volcanic-induced sulfate deposition values by the value produced at that site by the AD 1816 Tambora eruption, in order to reduce deposition differences among sites that might have been induced by differences in *local* site characteristics. This work revealed that most volcanic events in the early last millennium (AD



1000-1500) exhibited greater among-site variability in normalized sulphate deposition than was observed thereafter.

Citing Budner and Cole-Dai (2003) in noting that "the Antarctic polar vortex is involved in the distribution of stratospheric volcanic aerosols over the continent," Castellano *et al.* say that assuming the intensity and persistence of the polar vortex in both the troposphere and stratosphere "affect the penetration of air masses to inland Antarctica, isolating the continental area during cold periods and facilitating the advection of peripheral air masses during warm periods (Krinner and Genthon, 1998), we support the hypothesis that the pattern of volcanic deposition intensity and geographical variability [higher values at coastal sites] could reflect a warmer climate of Antarctica in the early last millennium," and that "the re-establishment of colder conditions, starting in about AD 1500, reduced the variability of volcanic depositions."

Describing this phenomenon in terms of what it implies, Castellano *et al.* say "this warm/cold step could be like a Medieval Climate Optimum-like to Little Ice Age-like transition." We agree, noting they additionally cite Goosse *et al.* (2004) as reporting evidence from Antarctic ice-core  $\delta D$  and  $\delta^{18}O$  data "in support of a Medieval Warming-like period in the Southern Hemisphere, delayed by about 150 years with respect to Northern Hemisphere Medieval Warming." Hence, the ten researchers conclude their report by postulating that "changes in the extent and intra-Antarctic variability of volcanic depositional fluxes may have been consequences of the establishment of a Medieval Warming-like period that lasted until about AD 1500."

A year later, Hall *et al.* (2006) collected skin and hair (and even some whole-body mummified remains) from Holocene raised-beach excavations at various locations along Antarctica's Victoria Land Coast, which they identified by both visual inspection and DNA analysis as coming from southern elephant seals, and which they analyzed for age by radiocarbon dating. By these means they obtained data from fourteen different locations within their study region -- which they describe as being "well south" of the seals' current "core sub-Antarctic breeding and molting grounds" -- that indicate that the period of time they denominate the *Seal Optimum* began about 600 BC and ended about AD1400, the latter of which dates they describe as being "broadly contemporaneous with the onset of Little Ice Age climatic conditions in the Northern Hemisphere and with glacier advance near [Victoria Land's] Terra Nova Bay."

In describing the significance of their findings, the US, British and Italian researchers say they are indicative of "warmer-than-present climate conditions" at the times and locations of the identified presence of the southern elephant seal, and that "if, as proposed in the literature, the [Ross] ice shelf survived this period, it would have been exposed to environments substantially warmer than present," which would have included both the Roman Warm Period and Medieval Warm Period.

Most recently, Williams *et al.* (2007) presented methyl chloride ( $CH_3Cl$ ) measurements of air extracted from a 300-m ice core that was obtained at the South Pole, Antarctica, covering the time period 160 BC to AD 1860. In describing what they found, the researchers say that " $CH_3Cl$  levels were elevated from 900-1300 AD by about 50 ppt relative to the previous 1000 years,

coincident with the warm Medieval Climate Anomaly (MCA)," and that they "decreased to a minimum during the Little Ice Age cooling (1650-1800 AD), before rising again to the modern atmospheric level of 550 ppt." Noting that "today, more than 90% of the CH<sub>3</sub>Cl sources and the majority of CH<sub>3</sub>Cl sinks lie between 30°N and 30°S (Khalil and Rasmussen, 1999; Yoshida *et al.*, 2004)," they say "it is likely that climate-controlled variability in CH<sub>3</sub>Cl reflects changes in tropical and subtropical conditions." In fact, they go so far as to state that "ice core CH<sub>3</sub>Cl variability over the last two millennia suggests a positive relationship between atmospheric CH<sub>3</sub>Cl and *global* [our italics] mean temperature."

As best we can determine from the graphical representation of their data, the peak CH<sub>3</sub>Cl concentration measured by Williams *et al.* during the MCA is approximately 533 ppt, which is within 3% of its current mean value of 550 ppt and well within the range of 520 to 580 ppt that characterizes methyl chloride's current variability. Hence, we may validly conclude that the mean peak temperature of the MCA (which we refer to as the Medieval Warm Period) over the latitude range 30°N to 30°S -- *and possibly over the entire globe* -- may not have been materially different from the mean peak temperature so far attained during the Current Warm Period. And this conclusion, along with the findings of the other studies we have reviewed, suggests there is nothing that is *unusual, unnatural or unprecedented* about the current level of earth's warmth, which further suggests that the historical increase in the atmosphere's CO<sub>2</sub> concentration may not have had anything to do with concomitant 20th-century global warming.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/a/antarcticmwp.php>.

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#### 4.8.4. Arctic

We begin our review of the Medieval Warm Period in the Arctic with the study of Dahl-Jensen *et al.* (1998), who used temperature measurements from two Greenland Ice Sheet boreholes to reconstruct the temperature history of this portion of the earth over the past 50,000 years. Their data indicate that after the termination of the glacial period, temperatures steadily rose to a maximum of 2.5°C warmer than at present during the Holocene Climatic Optimum (4,000 to 7,000 years ago). The Medieval Warm Period and Little Ice Age were also documented in the record, with temperatures 1°C warmer and 0.5-0.7°C cooler than at present, respectively. After

the Little Ice Age, they report that temperatures once again rose, but that they "have decreased during the last decades." These results thus clearly indicate that the Medieval Warm Period in this part of the Arctic was significantly warmer than it is there now.

Wagner and Melles (2001) also worked on Greenland, where they extracted a 3.5-m-long sediment core from a lake (Raffels So) on an island (Raffles O) located just off Liverpool Land on the east coast of Greenland, which they analyzed for a number of properties related to the past presence of seabirds there, obtaining a 10,000-year record that tells us much about the region's climatic history. Key to the study were biogeochemical data, which, in the words of the researchers, reflect "variations in seabird breeding colonies in the catchment which influence nutrient and cadmium supply to the lake."

Wagner and Melles' data reveal sharp increases in the values of the parameters they measured between about 1100 and 700 years before present (BP), indicative of the summer presence of significant numbers of seabirds during that "medieval warm period," as they describe it, which had been preceded by a several-hundred-year period (Dark Ages Cold Period) of little to no bird presence. Thereafter, their data suggest another absence of birds during what they call "a subsequent Little Ice Age," which they note was "the coldest period since the early Holocene in East Greenland."

The Raffels So data also show signs of a "resettlement of seabirds during the last 100 years, indicated by an increase of organic matter in the lake sediment and confirmed by bird observations." However, values of the most recent measurements are not as great as those obtained from the earlier Medieval Warm Period, which indicates that higher temperatures prevailed during the period from 1100 to 700 years BP than what has been observed over the most recent hundred years.

A third relevant Greenland study was conducted by Kaplan *et al.* (2002), who derived a climatic history of the Holocene by analyzing the physical-chemical properties of sediments obtained from a small lake in southern Greenland. They determined that the interval from 6000 to 3000 years BP was marked by warmth and stability, but that the climate cooled thereafter until its culmination in the Little Ice Age. From 1300-900 years BP, however, there was a partial amelioration during the Medieval Warm Period, which was associated with an approximate 1.5°C rise in temperature.

In a non-Greenland Arctic study, Jiang *et al.* (2002) analyzed diatom assemblages from a high-resolution core extracted from the seabed of the north Icelandic shelf to reconstruct a 4600-year history of mean summer sea surface temperature at that location. Starting from a maximum value of about 8.1°C at 4400 years BP, the climate was found to have cooled fitfully for about 1700 years and then more consistently over the final 2700 years of the record. The most dramatic departure from this long-term decline was centered on about 850 years BP, during the Medieval Warm Period, when *the temperature rose by more than 1°C above the line describing the long-term downward trend to effect an almost complete recovery from the colder temperatures of the Dark Ages Cold Period*, after which temperatures continued their descent

into the Little Ice Age, ending with a final most recent value of approximately 6.3°C. Hence, these data also clearly indicate that the Medieval Warm Period in this part of the Arctic was significantly warmer than it is there now.

Moving on, Moore *et al.* (2001) analyzed sediment cores from Donard Lake, Baffin Island, Canada, producing a 1240-year record of average summer temperatures for this Arctic region. Over the entire period from AD 750-1990, temperatures averaged 2.9°C. However, anomalously warm decades with summer temperatures as high as 4°C occurred around AD 1000 and 1100, while at the beginning of the 13th century, Donard Lake witnessed "one of the largest climatic transitions in over a millennium," as "average summer temperatures rose rapidly by nearly 2°C from 1195-1220 AD, ending in the warmest decade in the record" with temperatures near 4.5°C.

This rapid warming of the 13th century was followed by a period of extended warmth that lasted until an abrupt cooling event occurred around 1375 and made the following decade one of the coldest in the record. This event signaled the onset of the Little Ice Age, which lasted for 400 years, until a gradual warming trend began about 1800, which was followed by a dramatic cooling event in 1900 that brought temperatures back to levels similar to those of the Little Ice Age. This cold regime lasted until about 1950, whereupon temperatures warmed for about two decades but then tended downwards again all the way to the end of the record in 1990. Hence, in this part of the Arctic the Medieval Warm Period was also warmer than it is there currently. The following year, Grudd *et al.* (2002) assembled tree-ring widths from 880 living, dead, and subfossil northern Swedish pines into a continuous and precisely dated chronology covering the period 5407 BC to AD 1997. The strong association between these data and summer (June-August) mean temperatures of the last 129 years of the period then enabled them to produce a 7400-year history of summer mean temperature for northern Swedish Lapland.

The most dependable portion of this record, based upon the number of trees that were sampled, consisted of the last two millennia, which the authors say "display features of century-timescale climatic variation known from other proxy and historical sources, including a warm 'Roman' period in the first centuries AD and a generally cold 'Dark Ages' climate from about AD 500 to about AD 900." They also note that "the warm period around AD 1000 may correspond to a so-called 'Mediaeval Warm Period,' known from a variety of historical sources and other proxy records." Lastly, they say "the climatic deterioration in the twelfth century can be regarded as the starting point of a prolonged cold period that continued to the first decade of the twentieth century," which "Little Ice Age," in their words, is also "known from instrumental, historical and proxy records." Going back further in time, the tree-ring record displays several more of these relatively warmer and colder periods. And in a telling commentary on current climate-alarmist claims, they report that "the relatively warm conditions of the late twentieth century do not exceed those reconstructed for several earlier time intervals." In fact, the warmth of *many* of the earlier warm intervals significantly *exceeded* the warmth of the late 20th century.

Seppa and Birks (2002) used a recently developed pollen-climate reconstruction model and a new pollen stratigraphy from Toskaljavri -- a tree-line lake in the continental sector of northern Fennoscandia (located just above 69°N latitude) -- to derive quantitative estimates of annual precipitation and July mean temperature. As they describe it, their reconstructions "agree with the traditional concept of a 'Medieval Warm Period' (MWP) and 'Little Ice Age' in the North Atlantic region (Dansgaard *et al.*, 1975) and in northern Fennoscandia (Korhola *et al.*, 2000)." In addition, they report there is "a clear correlation between [their] MWP reconstruction and several records from Greenland ice cores," and that "comparisons of a smoothed July temperature record from Toskaljavri with measured borehole temperatures of the GRIP and Dye 3 ice cores (Dahl-Jensen *et al.*, 1998) and the  $\delta^{18}\text{O}$  record from the Crete ice core (Dansgaard *et al.*, 1975) show the strong similarity in timing of the MWP between the records." Last of all, they note that "July temperature values during the Medieval Warm Period (ca. 1400-1000 cal yr B.P.) were ca. 0.8°C higher than at *present*," where present means the last six decades of the 20th century.

Noting that temperature changes in *high latitudes* are (1) sensitive indicators of *global* temperature changes, and that they can (2) serve as a basis for verifying climate model calculations, Naurzbaev *et al.* (2002) developed a 2,427-year proxy temperature history for the part of the Taimyr Peninsula of northern Russia that lies between 70°30' and 72°28' North latitude, based on a study of ring-widths of living and preserved larch trees, noting further that "it has been established that the main driver of tree-ring variability at the polar timber-line [where they worked] is temperature (Vaganov *et al.*, 1996; Briffa *et al.*, 1998; Schweingruber and Briffa, 1996)." In doing so, they found that "the warmest periods over the last two millennia in this region were clearly in the third [Roman Warm Period], tenth to twelfth [Medieval Warm Period] and during the twentieth [Current Warm Period] centuries."

With respect to the second of these periods, they emphasize that "the warmth of the two centuries AD 1058-1157 and 950-1049 attests to the reality of relative mediaeval warmth in this region." Their data also reveal three other important pieces of information: (1) the Roman and Medieval Warm Periods were both warmer than the Current Warm Period has been to date, (2) the "beginning of the end" of the Little Ice Age was somewhere in the vicinity of 1830, and (3) the Current Warm Period peaked somewhere in the vicinity of 1940.

All of these observations are at odds with what is portrayed in the thousand-year Northern Hemispheric *hockeystick* temperature history of Mann *et al.* (1998, 1999) and its thousand-year global extension developed by Mann and Jones (2003), wherein (1) the Current Warm Period is depicted as the warmest such era of the past two millennia, (2) recovery from the Little Ice Age does not begin until after 1910, and (3) the Current Warm Period experiences its highest temperatures in the latter part of the 20th century's final decade.

Advancing two years closer to the present, Knudsen *et al.* (2004) documented climatic changes over the last 1200 years by means of high-resolution multi-proxy studies of benthic and planktonic foraminiferal assemblages, stable isotopes, and ice-rafted debris found in three sediment cores retrieved from the North Icelandic shelf. This work revealed that "the time

period between 1200 and around 7-800 cal. (years) BP, including the Medieval Warm Period, was characterized by relatively high bottom and surface water temperatures," after which "a general temperature decrease in the area marks the transition to ... the Little Ice Age." They also note that "minimum sea-surface temperatures were reached at around 350 cal. BP, when very cold conditions were indicated by several proxies." Thereafter, they say that "a modern warming of surface waters ... is *not* [our italics] registered in the proxy data," and that "there is no clear indication of warming of water masses in the area during the last decades," even in sea surface temperatures measured over the period 1948-2002.

Fast-forwarding another two years, Grinsted *et al.* (2006) developed "a model of chemical fractionation in ice based on differing elution rates for pairs of ions ... as a proxy for summer melt (1130-1990)," based on data obtained from a 121-meter-long ice core they extracted from the highest ice field in Svalbard (Lomonosovfonna: 78°51'53"N, 17°25'30"E), which was "validated against twentieth-century instrumental records and longer historical climate proxies." This history indicated that "in the oldest part of the core (1130-1200), the washout indices [were] more than 4 times as high as those seen during the last century, indicating a high degree of runoff." In addition, they report they have performed regular snow pit studies near the ice core site since 1997 (Virkkunen, 2004) and that "the very warm 2001 summer resulted in similar loss of ions and washout ratios as the earliest part of the core." They then state that "this suggests that the Medieval Warm Period in Svalbard summer conditions [was] as warm (or warmer) as present-day, consistent with the Northern Hemisphere temperature reconstruction of Moberg *et al.* (2005)." In addition, they conclude that "the degree of summer melt was significantly larger during the period 1130-1300 than in the 1990s," which likewise suggests that a *large portion* of the Medieval Warm Period was *significantly warmer* than the *peak* warmth (1990s) of the Current Warm Period.

Moving ahead a final two years, Besonen *et al.* (2008) derived thousand-year histories of varve thickness and sedimentation accumulation rate for Canada's Lower Murray Lake (81°20'N, 69°30'W), which is typically covered for about eleven months of each year by ice that reaches a thickness of 1.5 to 2 meters at the end of each winter. With respect to these parameters, they say -- citing seven other studies -- that "field-work on other High Arctic lakes clearly indicates that sediment transport and varve thickness are related to temperatures during the short summer season that prevails in this region, and we have no reason to think that this is not the case for Lower Murray Lake."

So what did they find? As the six scientists describe it, the story told by both the varve thickness and sediment accumulation rate histories of Lower Murray Lake is that "the twelfth and thirteenth centuries were relatively warm," and in this regard we note their data indicate that Lower Murray Lake and its environs were often *much* warmer during this time period (AD 1080-1320) than they were *at any point in the 20th century*, which has also been shown to be the case for Donard Lake (66.25°N, 62°W) by Moore *et al.* (2001).

In thus concluding this subsection, it is clear that the suite of measurements described in the studies reviewed above continues to indicate that the Arctic -- which climate models suggest

should be super-sensitive to greenhouse-gas-induced warming -- is *still* not as warm as it was many centuries ago during portions of the Medieval Warm Period, when there was *much* less CO<sub>2</sub> and methane in the air than there is today, which further suggests that the planet's more modest current warmth need not be the result of historical increases in these two trace gases of the atmosphere.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/a/arcticmwp.php>.

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#### 4.8.5. Asia

##### 4.8.5.1. China

Using a variety of climate records derived from peat, lake sediment, ice core, tree-ring and other proxy sources, Yang *et al.* (2002) identified a period of exceptional warmth throughout China between AD 800 and 1100. Yafeng *et al.* (1999) also observed a warm period between AD 970 and 1510 in  $\delta^{18}\text{O}$  data obtained from the Guliya ice cap of the Qinghai-Tibet Plateau. Similarly, Hong *et al.* (2000) developed a 6000-year  $\delta^{18}\text{O}$  record from plant cellulose deposited in a peat bog in the Jilin Province (42° 20' N, 126° 22' E), within which they found evidence of "an obvious warm period represented by the high  $\delta^{18}\text{O}$  from around AD 1100 to 1200 which may correspond to the Medieval Warm Epoch of Europe."

Shortly thereafter, Xu *et al.* (2002) determined from a study of plant cellulose  $\delta^{18}\text{O}$  variations in cores retrieved from peat deposits at the northeastern edge of the Qinghai-Tibet Plateau that from AD 1100-1300 "the  $\delta^{18}\text{O}$  of Hongyuan peat cellulose increased, consistent with that of Jinchuan peat cellulose and corresponding to the 'Medieval Warm Period'." In addition, Qian and Zhu (2002) analyzed the thickness of laminae in a stalagmite found in Shihua Cave, Beijing, from whence they inferred the existence of a relatively wet period running from approximately AD 940 to 1200.

Hong *et al.* (2000) also report that at the time of the MWP "the northern boundary of the cultivation of citrus tree (*Citrus reticulata* Blanco) and *Boehmeria nivea* (a perennial herb), both subtropical and thermophilous plants, moved gradually into the northern part of China, and it has been estimated that the annual mean temperature was 0.9-1.0°C higher than at present." Considering the climatic conditions required to successfully grow these plants, they further note that annual mean temperatures in that part of the country during the Medieval Warm Period must have been about 1.0°C higher than at present, with extreme January minimum temperatures fully 3.5°C warmer than they are today, citing De'er (1994).

Chu *et al.* (2002) studied the geochemistry of 1400 years of dated sediments recovered from seven cores taken from three locations in Lake Huguangyan (21°9'N, 110°17'E) on the low-lying Leizhou Peninsula in the tropical region of South China, together with information about the presence of snow, sleet, frost and frozen rivers over the past 1000 years obtained from historical documents. They report that "recent publications based on the phenological phenomena, distribution patterns of subtropical plants and cold events (Wang and Gong, 2000; Man, 1998; Wu and Dang, 1998; Zhang, 1994) argue for a warm period from the beginning of the tenth century AD to the late thirteenth century AD," as their own data also suggest. In addition, they note there was a major dry period from AD 880-1260, and that "local historical chronicles support these data, suggesting that the climate of tropical South China was dry during the 'Mediaeval Warm Period'."

Paulsen *et al.* (2003) used high-resolution  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  data derived from a stalagmite found in Buddha Cave [33°40'N, 109°05'E] to infer changes in climate in central China for the last 1270 years. Among the climatic episodes evident in their data were "those corresponding to the

Medieval Warm Period, Little Ice Age and 20th-century warming, lending support to the global extent of these events." In terms of timing, the dry-then-wet-then-dry-again MWP began about AD 965 and continued to approximately AD 1475.

Also working with a stalagmite, this one from Jingdong Cave about 90 km northeast of Beijing, Ma *et al.* (2003) assessed the climatic history of the past 3000 years at 100-year intervals on the basis of  $\delta^{18}\text{O}$  data, the Mg/Sr ratio, and the solid-liquid distribution coefficient of Mg. They found that between 200 and 500 years ago, "air temperature was about 1.2°C lower than that of the present," but that between 1000 and 1300 ago, there was an equally aberrant but *warm* period that "corresponded to the Medieval Warm Period in Europe."

Based on 200 sets of phenological and meteorological records extracted from a number of historical sources, many of which are described by Gong and Chen (1980), Man (1990, 2004), Sheng (1990) and Wen and Wen (1996), Ge *et al.* (2003) produced a 2000-year history of winter half-year temperature (October to April, when CO<sub>2</sub>-induced global warming is projected to be most evident) for the region of China bounded by latitudes 27 and 40°N and longitudes 107 and 120°E. Their work revealed a significant warm epoch that lasted from the AD 570s to the 1310s, the peak warmth of which was "about 0.3-0.6°C higher than present for 30-year periods, but over 0.9°C warmer on a 10-year basis."

Last of all, Bao *et al.* (2003) utilized proxy climate records (ice-core  $\delta^{18}\text{O}$ , peat-cellulose  $\delta^{18}\text{O}$ , tree-ring widths, tree-ring stable carbon isotopes, total organic carbon, lake water temperatures, glacier fluctuations, ice-core CH<sub>4</sub>, magnetic parameters, pollen assemblages and sedimentary pigments) obtained from twenty prior studies to derive a 2000-year temperature history of the northeastern, southern and western sections of the Tibetan Plateau. In each case, there was more than one prior 50-year period of time when the mean temperature of each region was warmer than it was over the most recent 50-year period. In the case of the northeastern sector of the Plateau, all of the maximum-warmth intervals occurred during the Medieval Warm Period; while in the case of the western sector, they occurred near the end of the Roman Warm Period, and in the case of the southern sector they occurred during both warm periods.

From these several studies, it is evident that for a considerable amount of time during the Medieval Warm Period, many, if not *most*, parts of China exhibited warmer conditions than those of modern times. And since those earlier high temperatures were obviously caused by something other than high atmospheric CO<sub>2</sub> concentrations, whatever was responsible for them could well be responsible for the warmth of today.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/m/mwpcchina.php>.

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#### 4.8.5.2. Russia

Demezhko and Shchapov (2001) studied a borehole extending to more than 5 km depth, reconstructing an 80,000-year history of ground surface temperature in the Middle Urals within the western rim of the Tagil subsidence (58°24' N, 59°44'E). The reconstructed temperature history revealed the existence of a number of climatic excursions, including, in their words, the "Medieval Warm Period with a culmination about 1000 years ago."

Further north, Hiller *et al.* (2001) analyzed subfossil wood samples from the Khibiny mountains on the Kola Peninsula of Russia (67-68°N, 33-34°E) in an effort to reconstruct the region's climate history over the past 1500 years. They determined that between AD 1000 and 1300 the tree-line was located at least 100-140 m *above* its current elevation. This observation, in their words, suggests that mean summer temperatures during this "Medieval climatic optimum" were "at least 0.8°C higher than today," and that "the Medieval optimum was the most pronounced warm climate phase on the Kola Peninsula during the last 1500 years."

Additional evidence for the Medieval Warm Period in Russia comes from Naurzbaev and Vaganov (2000), who developed a 2200-year proxy temperature record (212 BC to 1996 AD) using tree-ring data obtained from 118 trees near the upper timberline in Siberia. Based on their results, they concluded that the warming experienced in the 20th century was "not extraordinary," and that "the warming at the border of the first and second millennia was longer in time and similar in amplitude."

In concluding this brief review of Russian work, we highlight the study of Krenke and Chernavskaya (2002), who present an impressive overview of what is known about the MWP within Russia, as well as throughout the world, based on historical evidence, glaciological evidence, hydrologic evidence, dendrological data, archaeological data and palynological data. And what is known is that in many places it was warmer during the MWP than it was during the latter part of the 20th century. For example, they report that "the northern margin of boreal forests in Canada was shifted [north] by 55 km during the MWP, and the tree line in the Rocky Mountains in the southern United States and in the Krkonose Mountains was higher by 100-200 m than that observed at the present time."

In reference to the "hockeystick" temperature reconstruction of Mann *et al.* (1998, 1999), the two members of the Russian Academy of Sciences say "the temperature averaged over the 20th century was found to be the highest among all centennial means, although it remained within the errors of reconstructions for the early millennium." They pointedly remind us, however, that "one should keep in mind that the reconstructions of the early period were based nearly entirely on tree-ring data, which, because of the features of their interpretation, tend to underestimate low-frequency variations, so the temperatures of the Medieval Warm Period were possibly underestimated," after which they go on to provide yet additional evidence for that conclusion, reporting that "the limits of cultivated land or receding glaciers have not yet exceeded the level characteristic of the early millennium."

Concentrating on data wholly from within Russia, Krenke and Chernavskaya report large differences in a number of variables between the Little Ice Age (LIA) and MWP. With respect to the annual mean temperature of northern Eurasia, they report an MWP to LIA drop on the order of 1.5°C. They also say that "the frequency of severe winters reported was increased from once in 33 years in the early period of time, which corresponds to the MWP, to once in 20 years in the LIA," additionally noting that "the abnormally severe winters [of the LIA] were associated with the spread of Arctic air masses over the entire Russian Plain." Finally, they note that the data they used to draw these conclusions were "not used in the reconstructions performed by Mann *et al.*," which perhaps explains why the Mann *et al.* temperature history of the past millennium does not depict the coolness of the LIA or the warmth of the MWP nearly as well as the more appropriately derived temperature history of Esper *et al.* (2002).

In discussing their approach to the subject of global warming detection and attribution, the Russian Academicians state that "an analysis of climate variations over 1000 years should help ... reveal natural multicentennial variations possible at present but not detectable in available 100-200-year series of instrumental records." In this endeavor, they were highly successful, as their efforts have exposed the bankruptcy of the climate-alarmist claim that 20th-century warming is outside the realm of natural variability and must therefore be due to anthropogenic CO<sub>2</sub> emissions. Last of all, and in contradiction of another of Mann *et al.*'s contentions, Krenke and Chernavskaya unequivocally state, based on the results of their comprehensive study of the relevant scientific literature, that "the Medieval Warm Period and the Little Ice Age existed globally."

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/m/mwprussia.php>.

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### 4.8.5.3. Other Asia Locations

In addition to China and Russia, the Medieval Warm Period (MWP) has been identified in several other parts of Asia.

Schilman *et al.* (2001) analyzed foraminiferal oxygen and carbon isotopes, together with the physical and geochemical properties of sediments, contained in two cores extracted from the bed of the southeastern Mediterranean Sea off the coast of Israel, where they found evidence for the MWP centered around AD 1200. In discussing their findings, they note there is an abundance of other evidence for the existence of the MWP in the Eastern Mediterranean as well, including, in their words, "high Saharan lake levels (Schoell, 1978; Nicholson, 1980), high Dead Sea levels (Issar *et al.*, 1989, 1991; Issar, 1990, 1998; Issar and Makover-Levin, 1996), and high levels of the Sea of Galilee (Frumkin *et al.*, 1991; Issar and Makover-Levin, 1996)," in addition to "a precipitation maximum at the Nile headwaters (Bell and Menzel, 1972; Hassan, 1981; Ambrose and DeNiro, 1989) and in the northeastern Arabian Sea (von Rad *et al.*, 1999)."

Further to the east, Kar *et al.* (2002) explored the nature of climate change preserved in the sediment profile of an outwash plain two to three km from the snout of the Gangotri Glacier in the Uttarkashi district of Utranchal, Western Himalaya. Between 2000 and 1700 years ago, their data reveal the existence of a relatively cool climate. Then, from 1700 to 850 years ago, there was what they call an "amelioration of climate," during the transition from the depth of the Dark Ages Cold Period to the midst of the Medieval Warm Period. Subsequent to that time, Kar *et al.*'s data indicate the climate "became much cooler," indicative of its transition to Little Ice Age conditions, while during the last 200 years there has been a rather steady warming, as shown by Esper *et al.* (2002a) to have been characteristic of the entire Northern Hemisphere.

At a pair of other Asian locations, Esper *et al.* (2002b) used more than 200,000 ring-width measurements obtained from 384 trees at 20 individual sites ranging from the lower to upper timberline in the Northwest Karakorum of Pakistan (35-37°N, 74-76°E) and the Southern Tien Shan of Kirghizia (40°10'N, 72°35'E) to reconstruct regional patterns of climatic variations in Western Central Asia since AD 618. According to their analysis, the Medieval Warm Period was already firmly established and growing even warmer by the early 7th century; and between AD 900 and 1000, tree growth was exceptionally rapid, at rates that they say "cannot be observed during any other period of the last millennium."

Between AD 1000 and 1200, however, growing conditions deteriorated; and at about 1500, minimum tree ring-widths were reached that persisted well into the seventeenth century. Towards the end of the twentieth century, ring-widths increased once again; but Esper *et al.* (2002b) report that "the twentieth-century trend does not approach the AD 1000 maximum." In fact, there is almost no comparison between the two periods, with the Medieval Warm Period being far more conducive to good tree growth than the Modern Warm Period. As the authors describe the situation, "growing conditions in the twentieth century exceed the long-term average, but the amplitude of this trend is not comparable to the conditions around AD 1000."

The latest contribution to Asian temperature reconstruction is the study of Esper *et al.* (2003), who processed several extremely long juniper ring width chronologies for the Alai Range of the western Tien Shan in Kirghizia in such a way as to preserve multi-centennial growth trends that are typically "lost during the processes of tree ring data standardization and chronology building (Cook and Kairiukstis, 1990; Fritts, 1976)." In doing so, they used two techniques that maintain low frequency signals: long-term mean standardization (LTM) and regional curve standardization (RCS), as well as the more conventional spline standardization (SPL) technique that obscures (actually *removes*) long-term trends.

Carried back in time a full thousand years, the SPL chronologies depict significant inter-decadal variations but no longer-term trends. The LTM and RCS chronologies, on the other hand, show long-term decreasing trends from the start of the record until about AD 1600, broad minima from 1600 to 1800, and long-term increasing trends from about 1800 to the present. As a



result, in the words of Esper *et al.* (2003), "the main feature of the LTM and RCS Alai Range chronologies is a multi-centennial wave with high values towards both ends."

This grand result has essentially the same form as the Northern Hemisphere extratropic temperature history of Esper *et al.* (2002a), which is vastly different from the notorious hockeystick temperature history of Mann *et al.* (1998, 1999) and Mann and Jones (2003), in that it depicts the existence of both the Little Ice Age and preceding Medieval Warm Period, which are nowhere to be found in the Mann and Company reconstructions. In addition, the new result - especially the LTM chronology, which has a much smaller variance than the RCS chronology - depicts several periods in the first half of the last millennium that were *warmer* than *any* part of the last century. These periods include much of the latter half of the Medieval Warm Period and a good part of the first half of the 15th century, which has also been found to have been warmer than it is currently by McIntyre and McKittrick (2003) and by Loehle (2004).

In commenting on their important findings, Esper *et al.* (2003) remark that "if the tree ring reconstruction had been developed using 'standard' detrending procedures only, it would have been limited to inter-decadal scale variation and would have missed some of the common low frequency signal." We would also remark, with respect to the upward trend of their data since 1800, that a goodly portion of that trend may well have been due to the *aerial fertilization effect* of the concomitantly increasing atmospheric CO<sub>2</sub> content, which is known to greatly stimulate the growth of trees. Properly accounting for this very real effect would make the warmer-than-present temperatures of the first half of the past millennium *even warmer*, relative to those of the past century, than what they appear to be in Esper *et al.*'s LTM and RCS reconstructions.

In conclusion, as ever more data continue to accumulate, and as more correct procedures are employed to analyze them, the world's true temperature history is becoming ever more clear; and what's beginning to take shape will ultimately spell the end of the IPCC's ill-conceived rush to judgment on identifying both the nature and the cause of the post-Little Ice Age climatic amelioration.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/a/asiamwp.php>.

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#### 4.8.6. Europe

Based on analyses of subfossil wood samples from the Khibiny mountains on the Kola Peninsula of Russia, Hiller *et al.* (2001) were able to reconstruct a 1500-year history of alpine tree-line elevation. This record indicates that between AD 1000 and 1300, the tree-line there was located at least 100 to 140 meters *above* its current location. The researchers state that this fact implies a mean summer temperature that was "at least 0.8°C higher than today."

Moving from land to water, in a study of a well-dated sediment core from the Bornholm Basin in the southwestern Baltic Sea, Andren *et al.* (2000) found evidence for a period of high primary

production at approximately AD 1050. Many of the diatoms of that period were warm water species that the scientists say "cannot be found in the present Baltic Sea." This balmy period, they report, "corresponds to the time when the Vikings succeeded in colonizing Iceland and Greenland." The warmth ended rather abruptly, however, at about AD 1200, when they note there was "a major decrease in warm water taxa in the diatom assemblage and an increase in cold water taxa," which latter diatoms are characteristic of what they call the Recent Baltic Sea Stage that prevails to this day.

In another marine study, Voronina *et al.* (2001) analyzed dinoflagellate cyst assemblages in two sediment cores retrieved from the southeastern Barents Sea, one spanning a period of 8300 years and one spanning a period of 4400 years. The longer of the two cores indicated a warm interval from about 8000 to 3000 years before present, followed by cooling pulses coincident with lowered salinity and extended ice cover in the vicinity of 5000, 3500 and 2500 years ago. The shorter core additionally revealed cooling pulses at tentative dates of 1400, 300 and 100 years before present. For the bulk of the past 4400 years, however, *ice cover lasted only two to three months per year, as opposed to the modern mean of 4.3 months per year.* In addition, August temperatures ranged between 6 and 8°C, *significantly warmer than the present mean of 4.6°C.*

Moving back towards land, Mikalsen *et al.* (2001) made detailed measurements of a number of properties of sedimentary material extracted from the bottom of a fjord on the west coast of Norway, deriving a relative temperature history of the region that spanned the last five millennia. This record revealed the existence of a period stretching from A.D. 1330 to 1600 that, in their words, "had the highest bottom-water temperatures in Sulafjorden during the last 5000 years."

In eastern Norway, Nesje *et al.* (2001) analyzed a sediment core obtained from Lake Atnsjoen, deriving a 4500-year record of river flooding. They observed "a period of little flood activity around the Medieval period (AD 1000-1400)," which was followed by "a period of the most extensive flood activity in the Atnsjoen catchment." This flooding, in their words, resulted from the "post-Medieval climate deterioration characterized by lower air temperature, thicker and more long-lasting snow cover, and more frequent storms associated with the 'Little Ice Age'."

Working in both Norway and Scotland, Brooks and Birks (2001) studied midges, the larval-stage head capsules of which are well preserved in lake sediments and are, in their words, "widely recognized as powerful biological proxies for inferring past climate change." Applying this technique to sediments derived from a lake in the Cairngorms region of the Scottish Highlands, they determined that temperatures there peaked at about 11°C during what they refer to as the "Little Climatic Optimum" -- which we typically call the Medieval Warm Period -- "before cooling by about 1.5°C which may coincide with the 'Little Ice Age'."

These results, according to Brooks and Birks, "are in good agreement with a chironomid stratigraphy from Finse, western Norway (Velle, 1998)," where summer temperatures were "about 0.4°C warmer than the present day" during the Medieval Warm Period. This latter

observation also appears to hold for the Scottish site, since the upper sample of the lake sediment core from that region, which was collected in 1993, "reconstructs the modern temperature at about 10.5°C," which is 0.5°C less than the 11°C value the authors found for the Medieval Warm Period.

Moving to Switzerland, Filippi *et al.* (1999) analyzed a sediment core extracted from Lake Neuchatel in the western Swiss Lowlands. During this same transition from the Medieval Warm Period (MWP) to the Little Ice Age (LIA), they detected a drop of approximately 1.5°C in mean annual air temperature. To give some context to this finding, they say that "the warming during the 20th century does not seem to have fully compensated the cooling at the MWP-LIA transition." And to make the message even more clear, they add that during the Medieval Warm Period, the mean annual air temperature was "on average higher than at present."

Over in Ireland, in a cave in the southwestern part of the country, McDermott *et al.* (2001) derived a  $\delta^{18}\text{O}$  record from a stalagmite that provided evidence for climatic variations that are "broadly consistent with a Medieval Warm Period at  $\sim 1000 \pm 200$  years ago and a two-stage Little Ice Age." Also evident in the data were the  $\delta^{18}\text{O}$  signatures of the earlier Roman Warm Period and Dark Ages Cold Period that comprised the preceding millennial-scale cycle of climate in that region.

In another study of three stalagmites found in a cave in northwest Germany, Niggemann *et al.* (2003) discovered that the climate records they contained "resemble records from an Irish stalagmite (McDermott *et al.*, 1999)," specifically noting that their own records provide evidence for the existence of the Little Ice Age, the Medieval Warm Period and the Roman Warm Period, which evidence also implies the existence of what McDermott *et al.* (2001) call the Dark Ages Cold Period that separated the Medieval and Roman Warm Periods, as well as the existence of the unnamed cold period that preceded the Roman Warm Period.

Continuing our mini-review of the Medieval Warm Period in Europe, Bodri and Cermak (1999) derived individual ground surface temperature histories from the temperature-depth logs of 98 separate boreholes drilled in the Czech Republic. From these data they detected "the existence of a medieval warm epoch lasting from A.D. 1100-1300," which they describe as "one of the warmest postglacial times. Noting that this spectacular warm period was followed by the Little Ice Age, they went on to suggest that "the observed recent warming may thus be easily a natural return of climate from the previous colder conditions back to a 'normal'."

Filippi *et al.* (1999) share similar views, as is demonstrated by their citing of Keigwin (1996) to the effect that "sea surface temperature (SST) reconstructions show that SST was ca. 1°C cooler than today about 400 years ago and ca. 1°C warmer than today during the MWP." Citing Bond *et al.* (1997), they further note that the MWP and LIA are merely the most recent manifestations of "a pervasive millennial-scale coupled atmosphere-ocean climate oscillation," which, we might add, has absolutely nothing to do with variations in the air's CO<sub>2</sub> content.

Last of all, we report the findings of Berglund (2003), who identified several periods of expansion and decline of human cultures in northwest Europe and compared them with a history of reconstructed climate "based on insolation, glacier activity, lake and sea levels, bog growth, tree line, and tree growth." In doing so, he determined there was a positive correlation between human impact/land-use and climate change. Specifically, in the latter part of the record, where both cultural and climate changes were best defined, there was, in his words, a great "retreat of agriculture" centered on about AD 500, which led to "reforestation in large areas of central Europe and Scandinavia." He additionally notes that "this period was one of rapid cooling indicated from tree-ring data (Eronen *et al.*, 1999) as well as sea surface temperatures based on diatom stratigraphy in [the] Norwegian Sea (Jansen and Koc, 2000), which can be correlated with Bond's event 1 in the North Atlantic sediments (Bond *et al.*, 1997)."

Next came what Berglund calls a "boom period" that covered "several centuries from AD 700 to 1100." This interval of time proved to be "a favourable period for agriculture in marginal areas of Northwest Europe, leading into the so-called Medieval Warm Epoch," when "the climate was warm and dry, with high treelines, glacier retreat, and reduced lake catchment erosion." This period "lasted until around AD 1200, when there was a gradual change to cool/moist climate, the beginning of the Little Ice Age ... with severe consequences for the agrarian society."

In light of this varied array of empirical evidence, the story from Europe seems quite clear. There was a several-hundred-year period in the first part of the last millennium that was significantly warmer than it is currently, contrary to the claims of climate alarmists who say the warmth of that time was nothing special. In addition, there is reason to believe that the planet may be on a natural climate trajectory that is taking it back to a state reminiscent of the Medieval Warm Period, which we could call the Modern Warm Period. And there is nothing we can do about it *except*, as is implied by the study of Berglund (2003), *reap the benefits!*

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/e/europemwp.php>.

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#### 4.8.7. North America

What do studies of non-Arctic North America reveal about the nature of the Medieval Warm Period over this vast region?

Arseneault and Payette (1997) analyzed tree-ring and growth-form sequences obtained from more than 300 spruce remains buried in a presently treeless peatland in northern Quebec to produce a proxy record of climate for this region of the continent between 690 and 1591 AD. Perhaps the most outstanding feature of this history was the warm period it revealed between 860 and 1000 AD. Based on the fact that the northernmost 20th century location of the forest tree-line is presently 130 km *south* of their study site, the scientists concluded that the "Medieval Warm Period was approximately 1°C warmer than the 20th century."

Shifting to the other side of the continent, Calkin *et al.* (2001) carefully reviewed what they termed "the most current and comprehensive research of Holocene glaciation" along the northernmost Gulf of Alaska between the Kenai Peninsula and Yakutat Bay, where they too detected a Medieval Warm Period that lasted for "at least a few centuries prior to A.D. 1200." Also identifying the Medieval Warm Period, as well as other major warm and cold periods of the millennial-scale climatic oscillation that is responsible for them, was Campbell (2002), who analyzed the grain sizes of sediment cores obtained from Pine Lake, Alberta, Canada (52°N, 113.5°W) to provide a non-vegetation-based high-resolution record of climate variability for this part of North America over the past 4000 years. Periods of both increasing and decreasing grain size (related to moisture availability) were noted throughout the 4000-year record at decadal, centennial and millennial time scales. The most predominant departures were several-centuries-long epochs that corresponded to the Little Ice Age (about AD 1500-1900), the Medieval Warm Period (about AD 700-1300), the Dark Ages Cold Period (about BC 100 to AD 700) and the Roman Warm Period (about BC 900-100).

Working our way southward, Laird *et al.* (2003) studied diatom assemblages in sediment cores taken from three Canadian and three United States lakes situated within the northern prairies of North America, finding that "shifts in drought conditions on decadal through multicentennial scales have prevailed in this region for at least the last two millennia." In Canada, major shifts occurred near the beginning of the Medieval Warm Period, while in the United States they



occurred near its end. In giving some context to these findings, the authors state that "distinct patterns of abrupt change in the Northern Hemisphere are common at or near the termination of the Medieval Warm Period (*ca.* A.D. 800-1300) and the onset of the Little Ice Age (*ca.* A.D. 1300-1850)." They also note that "millennial-scale shifts over at least the past 5,500 years, between sustained periods of wetter and drier conditions, occurring approximately every 1,220 years, have been reported from western Canada (Cumming *et al.*, 2002)," and that "the striking correspondence of these shifts to large changes in fire frequencies, inferred from two sites several hundreds of kilometers to the southwest in the mountain hemlock zone of southern British Columbia (Hallett *et al.*, 2003), suggests that these millennial-scale dynamics are linked and operate over wide spatial scales."

In an effort to determine whether these climate-driven millennial-scale cycles are present in the terrestrial pollen record of North America, Viau *et al.* (2002) analyzed a set of 3,076 <sup>14</sup>C dates from the North American Pollen Database used to date sequences in more than 700 pollen diagrams across North America. Results of their statistical analyses indicated there were nine millennial-scale oscillations during the past 14,000 years in which continent-wide synchronous vegetation changes with a periodicity of roughly 1650 years were recorded in the pollen records. The most recent of the vegetation transitions was centered at approximately 600 years BP (before present). This event, in the words of the authors, "culminat[ed] in the Little Ice Age, with maximum cooling 300 years ago." Prior to that event, a major transition that began approximately 1600 years BP represents the climatic amelioration that "culminat[ed] in the maximum warming of the Medieval Warm Period 1000 years ago."

And so it goes, on back through the Holocene and into the preceding late glacial period, with the times of all major pollen transitions being "consistent," in the words of the authors of the study, "with ice and marine records." Viau *et al.* additionally note that "the large-scale nature of these transitions and the fact that they are found in different proxies confirms the hypothesis that Holocene and late glacial climate variations of millennial-scale were abrupt transitions between climatic regimes as the atmosphere-ocean system reorganized in response to some forcing." They go on to say that "although several mechanisms for such *natural* [our italics] forcing have been advanced, recent evidence points to a potential solar forcing (Bond *et al.*, 2001) associated with ocean-atmosphere feedbacks acting as global teleconnections agents." Furthermore, they note that "these transitions are identifiable across North America and presumably the world."

Additional evidence for the solar forcing of these millennial-scale climate changes is provided by Shindell *et al.* (2001), who used a version of the Goddard Institute for Space Studies GCM to estimate climatic differences between the period of the Maunder Minimum in solar irradiance (mid-1600s to early 1700s) and a century later, when solar output was relatively high for several decades. Their results compared so well with historical and proxy climate data that they concluded, in their words, that "colder winter temperatures over the Northern Hemispheric continents during portions of the 15th through the 17th centuries (sometimes called the Little Ice Age) and warmer temperatures during the 12th through 14th centuries (the putative Medieval Warm Period) may have been influenced by long-term solar variations."

Rounding out our mini-review of the Medieval Warm Period in North America are two papers dealing with the climatic history of the Chesapeake Bay region of the United States. The first, by Brush (2001), consists of an analysis of sediment cores obtained from the Bay's tributaries, marshes and main stem that covers the past millennium, in which it is reported that "the Medieval Climatic Anomaly and the Little Ice Age are recorded in Chesapeake sediments by terrestrial indicators of dry conditions for 200 years, beginning about 1000 years ago, followed by increases in wet indicators from about 800 to 400 years ago."

Willard *et al.* (2003) studied the same region for the period 2300 years BP to the present, via an investigation of fossil dinoflagellate cysts and pollen from sediment cores. Their efforts revealed that "several dry periods ranging from decades to centuries in duration are evident in Chesapeake Bay records." The first of these periods of lower-than-average precipitation, which spanned the period 200 BC-AD 300, occurred during the latter part of the Roman Warm Period, as delineated by McDermott *et al.* (2001) on the basis of a high-resolution speleothem  $\delta^{18}\text{O}$  record from southwest Ireland. The next such dry period (~AD 800-1200), in the words of the authors, "corresponds to the 'Medieval Warm Period', which has been documented as drier than average by tree-ring (Stahle and Cleaveland, 1994) and pollen (Willard *et al.*, 2001) records from the southeastern USA."

Willard *et al.* go on to say that "mid-Atlantic dry periods generally correspond to central and southwestern USA 'megadroughts', described by Woodhouse and Overpeck (1998) as major droughts of decadal or more duration that probably exceeded twentieth-century droughts in severity." They further indicate that "droughts in the late sixteenth century that lasted several decades, and those in the 'Medieval Warm Period' and between ~AD 50 and AD 350 spanning a century or more have been indicated by Great Plains tree-ring (Stahle *et al.*, 1985; Stahle and Cleaveland, 1994), lacustrine diatom and ostracode (Fritz *et al.*, 2000; Laird *et al.*, 1996a, 1996b) and detrital clastic records (Dean, 1997)."

In summing up these several findings, it is evident that the Medieval Warm Period has left its mark throughout North America in the form of either warm temperature anomalies or periods of relative dryness.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/n/northamericawp.php>.

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#### 4.8.8. South America

Was there a Medieval Warm Period anywhere in addition to the area surrounding the North Atlantic Ocean, where its occurrence is uncontested? This question is of utmost importance to the ongoing global warming debate, since if there was, and if the locations where it occurred were as warm then as they are currently, there is no need to consider the temperature increase of the past century as anything other than the natural progression of the persistent millennial-scale oscillation of climate that regularly brings the earth several-hundred-year periods of modestly higher and lower temperatures that are totally independent of variations in atmospheric CO<sub>2</sub> concentration. Hence, we here consider this question as it applies to South America, a region far removed from the lands where the existence of the Medieval Warm Period was first recognized.

In Argentina, Cioccale (1999) assembled what was known at the time about the climatic history of the central region of that country over the past 1400 years, highlighting a climatic "improvement" that began some 400 years before the start of the last millennium, which ultimately came to be characterized by "a marked increase of environmental suitability, under a relatively homogeneous climate." As a result of this climatic amelioration that marked the transition of the region from the Dark Ages Cold Period to the Medieval Warm Period, Cioccale says "the population located in the lower valleys ascended to higher areas in the Andes," where they remained until around AD 1320, when the transition to the stressful and extreme climate of the Little Ice Age began.

Down at the southern tip of the country in Tierra del Fuego, Mauquoy *et al.* (2004) inferred similar changes in temperature and/or precipitation from plant macrofossils, pollen, fungal spores, testate amebae and humification associated with peat monoliths collected from the Valle de Andorra. These new chronologies were compared with other chronologies of pertinent data from both the Southern and Northern Hemispheres in an analysis that indicated there was evidence for a period of warming-induced drier conditions from AD 960-1020, which, in their words, "seems to correspond to the Medieval Warm Period (MWP, as derived in the Northern Hemisphere)." They note that "this interval compares well to the date range of AD 950-1045 based on Northern Hemisphere extratropical tree-ring data (Esper *et al.*, 2002)," and they conclude that this correspondence "shows that the MWP was possibly synchronous in both hemispheres, as suggested by Villalba (1994)."

In Chile, Jenny *et al.* (2002) studied geochemical, sedimentological and diatom-assemblage data derived from sediment cores extracted from one of the largest natural lakes (Laguna Aculeo) in the central part of the country. From 200 BC, when the record began, until AD 200, conditions there were primarily dry, during the latter stages of the Roman Warm Period. Subsequently, from AD 200-700, with a slight respite in the central hundred years of that period, there was a high frequency of flood events, during the Dark Ages Cold Period. Then came a several-hundred-year period of less flooding that was coeval with the Medieval Warm Period. This more benign period was then followed by another period of frequent flooding from 1300-1700 that was coincident with the Little Ice Age, after which flooding picked up again after 1850.

In Peru, Chepstow-Lusty *et al.* (1998) derived a 4000-year climate history from a study of pollen in sediment cores obtained from a recently in-filled lake in the Patacancha Valley near Marcacocha. Their data indicated a several-century decline in pollen content after AD 100, as the Roman Warm Period gave way to the long and dreary Dark Ages Cold Period. However, a "more optimum climate," as they describe it, with warmer temperatures and drier conditions, came into being and prevailed for several centuries after about AD 900, which was, of course, the Medieval Warm Period, which was followed by the Little Ice Age, all of which climatic periods are in nearly perfect temporal agreement with the climatic history derived by McDermott *et al.* (2001) from a study of a stalagmite recovered from a cave nearly half the world away in Ireland.

Subsequent work in this area was conducted by Chepstow-Lusty and Winfield (2000) and Chepstow-Lusty *et al.* (2003). Centered on approximately 1000 years ago, the former researchers identified what they describe as "the warm global climatic interval frequently referred to as the Medieval Warm Epoch." This extremely *arid* interval in this part of South America, in their opinion, may have played a significant role in the collapse of the Tiwanaku civilization further south, where a contemporaneous prolonged drought occurred in and around the area of Lake Titicaca (Binford *et al.*, 1997; Abbott *et al.*, 1997).

Near the start of this extended dry period, which had gradually established itself between about AD 700 and 1000, Chepstow-Lusty and Winfield report that "temperatures were beginning to increase after a sustained cold period that had precluded agricultural activity at

these altitudes." This earlier colder and wetter interval was coeval with the Dark Ages Cold Period of the North Atlantic region, which in the Peruvian Andes had held sway for a good portion of the millennium preceding AD 1000, as revealed by a series of climatic records developed from sediment cores extracted from yet other lakes in the Central Peruvian Andes (Hansen *et al.*, 1994) and by proxy evidence of concomitant Peruvian glacial expansion (Wright, 1984; Seltzer and Hastorf, 1990).

Preceding the Dark Ages Cold Period in both parts of the world was what in the North Atlantic region is called the Roman Warm Period. This well-defined climatic epoch is also strikingly evident in the pollen records of Chepstow-Lusty *et al.* (2003), straddling the BC/AD calendar break with one to two hundred years of relative warmth and significant aridity on both sides of it.

Returning to the Medieval Warm Period and preceding towards the present, the data of Chepstow-Lusty *et al.* (2003) reveal the occurrence of the Little Ice Age, which in the Central Peruvian Andes was characterized by relative coolness and wetness. These characteristics of that climatic interval are also evident in ice cores retrieved from the Quelccaya ice cap in southern Peru, the summit of which extends 5670 meters above mean sea level (Thompson *et al.*, 1986, 1988). Finally, both the Quelccaya ice core data and the Marcacocha pollen data reveal the transition to the drier Modern Warm Period that occurred over the past 100-plus years.

In harmony with these several findings are the related observations of Rein *et al.* (2004), who derived a high-resolution flood record of the entire Holocene from an analysis of the sediments in a 20-meter core retrieved from a sheltered basin situated on the edge of the Peruvian shelf about 80 km west of Lima. These investigators found a major Holocene anomaly in the flux of lithic components from the continent onto the Peruvian shelf during the Medieval period. Specifically, they report that "lithic concentrations were very low for about 450 years during the Medieval climatic anomaly from A.D. 800 to 1250." In fact, they state that "all known terrestrial deposits of El Niño mega-floods (Magillian and Goldstein, 2001; Wells, 1990) precede or follow the medieval anomaly in our marine records and none of the El Niño mega-floods known from the continent date within the marine anomaly." In addition, they report that "this precipitation anomaly also occurred in other high-resolution records throughout the ENSO domain," citing eleven other references in support of this statement.

Consequently, because heavy winter rainfalls along and off coastal Peru only occur during times of maximum El Niño strength, and because El Niños are typically more prevalent and stronger during cooler as opposed to warmer periods (see El Niño (Relationship to Global Warming) in Chapter 5), the *lack* of strong El Niños from A.D. 800 to 1250 suggests that this period was truly a Medieval *Warm* Period; and the significance of this observation was not lost on Rein *et al.* In the introduction to their paper, for example, they note that "discrepancies exist between the Mann curve and alternative time series for the Medieval period." *Most notably*, to use their words, "the global Mann curve has no temperature optimum, whereas the Esper *et al.* (2002) reconstruction shows northern hemisphere temperatures almost as high as those of the 20th

century" during the Medieval period. As a result, in the final sentence of their paper they suggest that "the occurrence of a Medieval climatic anomaly (A.D. 800-1250) with persistently weak El Niños may therefore assist the interpretation of some of the regional discrepancies in thermal reconstructions of Medieval times," which is a polite way of suggesting that the Mann *et al.* (1998, 1999) hockeystick temperature history is deficient in not depicting the presence of a true Medieval *Warm* Period.

In Venezuela, Haug *et al.* (2001) found a temperature/precipitation relationship that was different from that of the rest of the continent. In examining the titanium and iron concentrations of an ocean sediment core taken from the Cariaco Basin on the country's northern shelf, they determined that the concentrations of these elements were *lower* during the Younger Dryas *cold* period between 12.6 and 11.5 thousand years ago, corresponding to a *weakened* hydrologic cycle with *less* precipitation and runoff, while during the *warmth* of the Holocene Optimum of 10.5 to 5.4 thousand years ago, titanium and iron concentrations remained at or near their *highest* values, suggesting *wet* conditions and an *enhanced* hydrologic cycle. Closer to the present, *higher* precipitation was also noted during the Medieval Warm Period from 1.05 to 0.7 thousand years ago, followed by *drier* conditions associated with the Little Ice Age between 550 and 200 years ago.

In an update of this study, Haug *et al.* (2003) developed a hydrologic history of pertinent portions of the record that yielded "roughly bi-monthly resolution and clear resolution of the annual signal." This record revealed that "before about 150 A.D.," which according to the climate history of McDermott *et al.* corresponds to the latter portion of the Roman Warm Period (RWP), Mayan civilization had *flourished*. However, during the transition to the Dark Ages Cold Period (DACP), which was accompanied by a slow but long decline in precipitation, Haug *et al.* report that "the first documented historical crisis hit the lowlands, which led to the 'Pre-Classic abandonment' (Webster, 2002) of major cities."

This crisis occurred during the first intense multi-year drought of the RWP-to-DACP transition, which was centered on about the year 250 A.D. Although the drought was devastating to the Maya, Haug *et al.* report that when it was over, "populations recovered, cities were reoccupied, and Maya culture blossomed in the following centuries during the so-called Classic period." Ultimately, however, there came a time of total reckoning, between about 750 and 950 A.D., during what Haug *et al.* determined was the driest interval of the entire Dark Ages Cold Period, when they report that "the Maya experienced a demographic disaster as profound as any other in human history," in response to a number of other intense multi-year droughts. During this Terminal Classic Collapse, as it is called, Haug *et al.* say that "many of the densely populated urban centers were abandoned permanently, and Classic Maya civilization came to an end."

In assessing the significance of these several observations near the end of their paper, Haug *et al.* conclude that the latter droughts "were the most severe to affect this region in the first millennium A.D." Although some of these spectacular droughts were "brief," lasting "only" between three and nine years, Haug *et al.* report "they occurred during an extended period of reduced overall precipitation that may have already pushed the Maya system to the verge of

collapse," which suggests that these *droughts within dry periods* were likely the proverbial straws that broke the camel's back.

Although the Mayan civilization thus faded away, Haug *et al.*'s data soon thereafter depict the development of the Medieval Warm Period, when the Vikings established their historic settlement on Greenland. Then comes the Little Ice Age, which just as quickly led to the Vikings demise in that part of the world. This distinctive cold interval of the planet's millennial-scale climatic oscillation must have also led to hard times for the people of Mesoamerica and northern tropical South America; for according to the data of Haug *et al.*, the Little Ice Age produced *by far* the lowest precipitation regime (of several hundred years duration) of the last two millennia in that part of the world.

In conclusion, it is difficult to believe that the *strong synchronicity* of the century-long Northern Hemispheric and South American warm and cold periods described above was coincidental. It is much more realistic to believe it was the result of a millennial-scale oscillation of climate that is global in scope and driven by some regularly-varying forcing factor. Although one can argue about the identity of that forcing factor and the means by which it exerts its influence, one thing should be clear: *it is not the atmosphere's CO<sub>2</sub> concentration*, which has only exhibited a significant in-phase variation with global temperature change over the Little Ice Age to Modern Warm Period transition. This being the case, it should be clear that the climatic amelioration of the past century or more has had nothing to do with the concomitant rise in the air's CO<sub>2</sub> content but *everything* to do with the influential forcing factor that has governed the millennial-scale oscillation of earth's climate as far back in time as we have been able to detect it.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/s/southamericampwp.php>.

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#### **4.9. Atmospheric Methane**

In Chapter 2 of this document, we reported on several real-world phenomena that can act to reduce or extract methane (CH<sub>4</sub>) from the atmosphere, most of which feedbacks are enhanced as the air's CO<sub>2</sub> concentration rises. That those feedbacks may already be operating and having a significant impact on global methane concentrations is illustrated in a discussion of observed atmospheric methane trends.

Up until recently, the Intergovernmental Panel on Climate Change (IPCC) has long predicted that earth's tropospheric methane concentration would rise dramatically throughout the 21st century; see, for example, Ehhalt and Prather (2001). Today, most models still project methane concentrations will rise above the current 1.77 ppm value by 2100, perhaps doubling, albeit some models project it will stabilize or fall slightly. Why is the atmospheric methane concentration so important? Because methane's contribution to anthropogenic radiative forcing, including direct and indirect effects, is about 0.7 W m<sup>-2</sup>, which amounts to about half that of CO<sub>2</sub>. Thus, getting the *right* methane concentration at any point in the future is crucial for all model-based predictions of global temperature. In the present section we review observed trends in this important greenhouse gas over the past quarter-century.

We begin with the graph of real-world data from Simpson *et al.* (2002), reproduced on the next page as Figure 4.9.1, which clearly shows a linear-trend decline in CH<sub>4</sub> growth rates since the mid-1980s, which at the time of their publication, they vehemently contended was "premature to believe," even though their own data bore witness against them in demonstrating that such was in fact occurring.

With respect to these data, and especially the data from the 1990s, Simpson *et al.* cautioned “against viewing each year of high CH<sub>4</sub> growth as an anomaly against a trend of declining CH<sub>4</sub> growth.” Yet that is *precisely* what the data suggest, to us at least, i.e., a declining baseline upon which are superimposed periodic anomalous growth-rate spikes.

In this interpretation, however, we are not alone. The first of the 1990s’ large CH<sub>4</sub> spikes is widely recognized as having been caused by the eruption of Mt. Pinatubo in June of 1991 (Bekki *et al.*, 1994; Dlugokencky *et al.*, 1996; Lowe *et al.*, 1997); while the last and most dramatic of the spikes has been linked to the remarkably strong El Niño of 1997-98 (Dlugokencky *et al.*, 2001). Furthermore, as noted earlier, Dlugokencky *et al.* (1998), Francey *et al.* (1999) and Lassey *et al.* (2000) have all felt confident in interpreting the data in such a way as to suggest that the annual rate-of-rise of the atmosphere’s CH<sub>4</sub> concentration is indeed declining and leading to a cessation of growth in the atmospheric burden of methane.

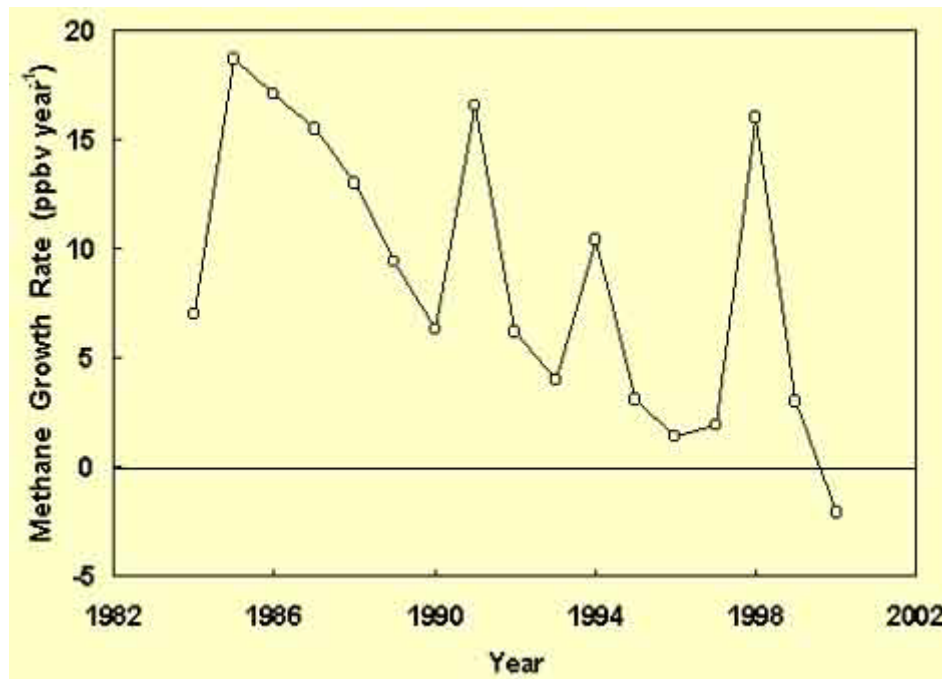


Figure 4.9.1. Global tropospheric methane (CH<sub>4</sub>) growth rate vs. time.  
Adapted from Simpson *et al.* (2002).

Projecting ahead, therefore, if anomalous events such as those recorded in the 1990s continue to occur at similar intervals, the global atmospheric CH<sub>4</sub> concentration should continue to rise - but only very slowly - for just a few more years, after which the declining background CH<sub>4</sub> growth rate, which may have already turned negative, will have dropped low enough to have the capacity to totally overwhelm any short-term positive impacts of periodic anomalous CH<sub>4</sub>

spikes. Then we should be able to see an actual decline in the atmosphere's global  $\text{CH}_4$  concentration, which should gradually accelerate in the negative direction, as subsequent anomalous  $\text{CH}_4$  spikes fail to penetrate into positive territory. This projection, in our opinion, is not only plausible, but is the one most likely to ultimately be found to be correct, based on what we feel is the most rational interpretation of the data portrayed in the preceding figure.

Subsequent to the publication of Simpson *et al.*'s study, Dlugokencky *et al.* (2003) revisited the subject with an additional two years' of data. Based on measurements from 43 globally-distributed remote boundary-layer sites that were obtained by means of the methods of Dlugokencky *et al.* (1994), they defined an evenly-spaced matrix of surface  $\text{CH}_4$  mole fractions as a function of time and latitude, from which they calculated global  $\text{CH}_4$  concentration averages for the years 1984-2002. We have extracted their results from their graphical presentation and re-plotted them as shown in Figure 4.9.2. below, where it can be seen that they fall into three natural groupings: initial and latter stages, to which we have fit linear regressions, and an intervening middle stage, to which we have fit a second-order polynomial.

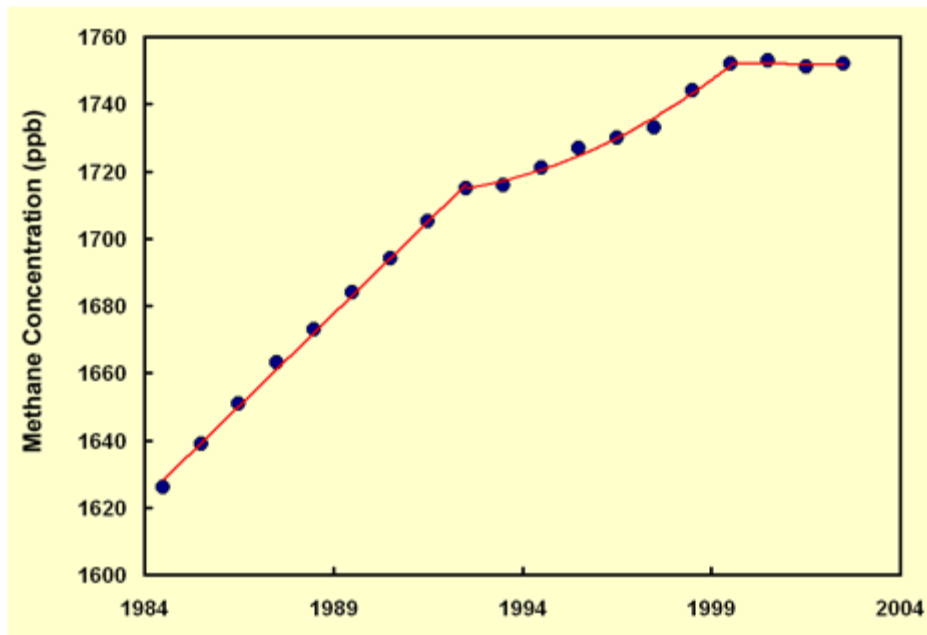
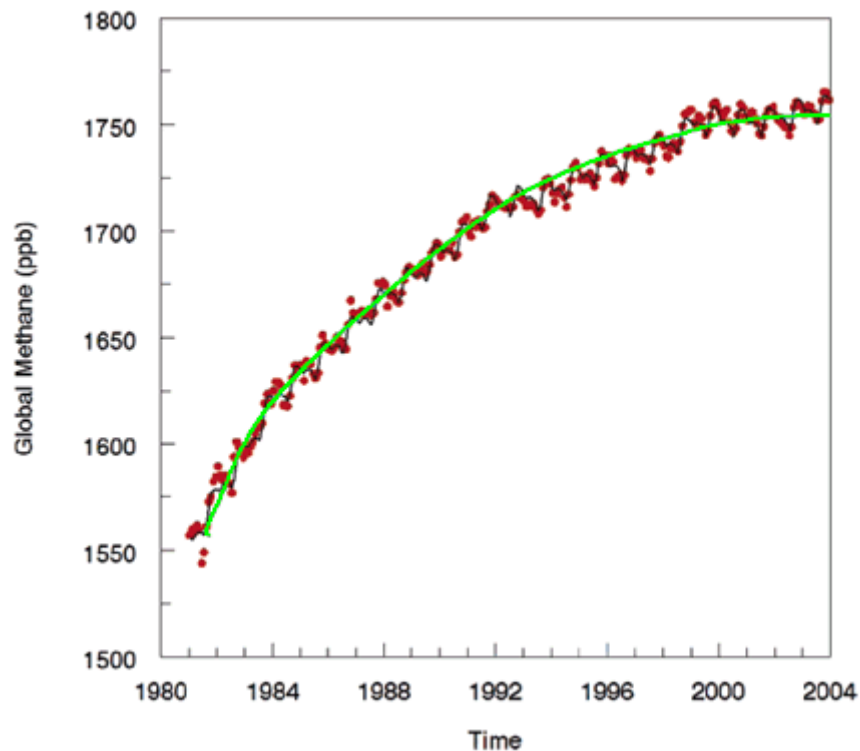


Figure 4.9.2. *Global tropospheric methane ( $\text{CH}_4$ ) concentration vs. time.*  
Adapted from Dlugokencky *et al.* (2003).

With respect to these data, Dlugokencky *et al.* note that the globally-averaged atmospheric methane concentration "was constant at ~1751 ppb from 1999 through 2002," which suggests, in their words, that "during this 4-year period the global methane budget has been at steady state." They caution, however, that "our understanding is still not sufficient to tell if the prolonged pause in  $\text{CH}_4$  increase is temporary or permanent." We agree. However, based on the fact that the data describe an initial stage of significant yearly  $\text{CH}_4$  increase, a subsequent stage of much smaller yearly  $\text{CH}_4$  increase, and a latter stage of no yearly  $\text{CH}_4$  increase, we feel

confident in suggesting that if the recent pause in  $\text{CH}_4$  increase is indeed temporary, it will likely be followed by a decrease in  $\text{CH}_4$  concentration, since that would be the next logical step in the observed progression from significant, to much smaller to no yearly  $\text{CH}_4$  increase.

In the next finding on the subject, Khalil *et al.* (2007) essentially “put the nails in the coffin” of the idea that rising atmospheric  $\text{CH}_4$  concentrations pose any further global warming threat at all. In their study, the three Oregon (USA) researchers combined two huge atmospheric methane data sets to produce the unified dataset depicted in Figure 4.9.3. below.

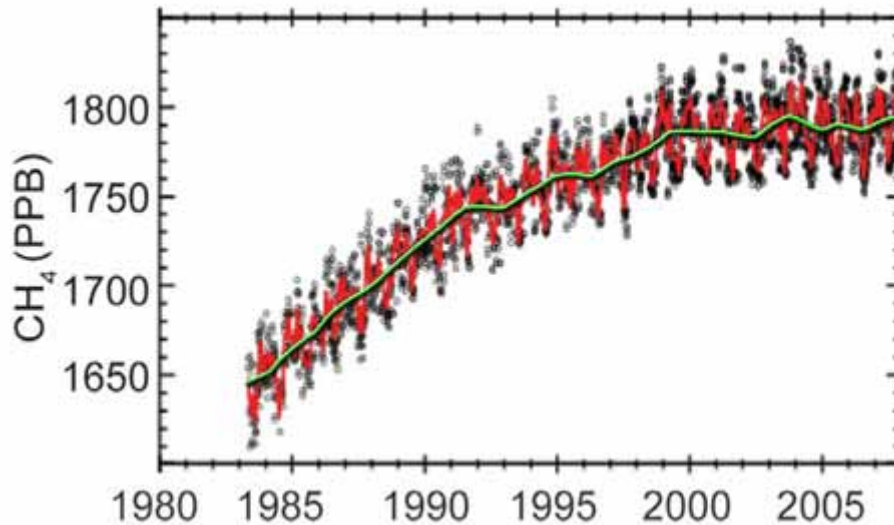


**Figure 4.9.3.** *Global methane ( $\text{CH}_4$ ) concentration. Adapted from Khalil et al. (2007).*

In viewing this graph, to which we have added the smooth green line, it is again clear that the rate of methane increase in the atmosphere has dropped dramatically over time. As Khalil *et al.* describe it, “the trend has been decreasing for the last two decades until the present when it has reached near zero,” and they go on to say that “it is questionable whether human activities can cause methane concentrations to increase greatly in the future.”

One year later, Schnell and Dlugokencky (2008) provided an update through 2007 of atmospheric methane concentrations as determined from weekly discrete samples collected on

a regular basis since 1983 at the NOAA/ESRL Mauna Loa Observatory. Our adaptation of the graphical rendition of the data provided by the authors is presented in Figure 4.9.4. below.



**Figure 4.9.4.** Trace gas mole fractions of methane ( $\text{CH}_4$ ) as measured at Mauna Loa, Hawaii. Adapted from Schnell and Dlugokencky (2008).

In commenting on the data contained in the figure above, Schnell and Dlugokencky state that "atmospheric  $\text{CH}_4$  has remained nearly constant since the late 1990s." This is a most important finding, because, as they also note, "methane's contribution to anthropogenic radiative forcing, including direct and indirect effects, is about  $0.7 \text{ W m}^{-2}$ , about half that of  $\text{CO}_2$ ." In addition, they say that "the increase in methane since the preindustrial era is responsible for approximately one-half the estimated increase in background tropospheric  $\text{O}_3$  during that time."

Lastly, Rigby *et al.* analyzed methane data obtained from the Advanced Global Atmospheric Gases Experiment (AGAGE) and the Australian Commonwealth Scientific and Industrial Research Organization (CSIRO) over the period January 1997 to April 2008. The results of their analysis indicated that methane concentrations "show renewed growth from the end of 2006 or beginning of 2007 until the most recent measurements," with the record-long range of methane growth rates mostly hovering about zero, but sometimes dropping five parts per billion (ppb) per year into the negative range, while rising near the end of the record to mean positive values of 8 and 12 ppb per year for the two measurement networks.

Although some people might be alarmed by these findings, as well as by the US, UK and Australian researchers' concluding statement that the methane growth rate during 2007 "was significantly elevated at all AGAGE and CSIRO sites simultaneously for the first time in almost a decade," there is also *reassurance* in the recent findings. We note, for example, that near the end of 1998 and the beginning of 1999, both networks measured even *larger* methane growth rate increases of approximately 13 ppb per year, before dropping back to zero at the beginning of the new millennium. And we note that the most current displayed data from the two networks indicate the beginning of what could well be another downward trend.

Additional reassurance in this regard comes from the work of Simpson *et al.* (2002), the findings of whom we reproduced previously in Figure 4.9.1. As can be seen there, even *greater* methane growth rates than those observed by Rigby *et al.* occurred in still earlier years. Hence, these periodic one-year-long upward spikes in methane growth rate must be the result of some *normal phenomenon*, the identity of which, however, has yet to be determined.

In light of these finding, it can be appreciated that over the past decade there have been essentially *no increases* in these two negative impacts of methane emissions to the atmosphere, and that the leveling out of the atmosphere's methane concentration -- the exact causes of which, in the words of Schnell and Dlugokencky, "are still unclear" -- has resulted in a full *one-third reduction* in the combined radiative forcing that would otherwise have been produced by a continuation of the prior rates-of-rise of the concentrations of the two atmospheric greenhouse gases.

The above observations are especially important given that most CH<sub>4</sub> emission scenarios considered by the IPCC result in increasing atmospheric CH<sub>4</sub> for at least the next 3 decades, and many of the scenarios projected large increases through the 21st century. Hence, if the future course of atmospheric CH<sub>4</sub> concentration will be to *decline*, or at least rise no higher, the IPCC is *way off base*, and there will be a significant natural amelioration of a large portion of the many deleterious consequences the IPCC projects.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/m/methaneatmos.php>.

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## 5. EXTREME WEATHER

### 5.1. Drought

One of the many dangers of global warming, according to the world's climate alarmists, is the predicted propensity for rising temperatures to produce more frequent, more severe, and longer-lasting droughts almost everywhere on earth. But just how realistic are the climate models upon which these claims are based? And what does real-world climatic *history* have to say about the subject? In this section, we discuss the findings of several scientific papers that broach these questions as they pertain to various regions across the earth, beginning with Africa.

Additional information on this topic, including reviews on drought not discussed here, can be found at [http://www.co2science.org/subject/d/subject\\_d.php](http://www.co2science.org/subject/d/subject_d.php) under the heading Drought.

#### 5.1.1. Africa

One of the more recent of these papers (Lau *et al.*, 2006) is entitled "A multimodel study of the twentieth-century simulations of Sahel drought from the 1970s to 1990s." The purpose of the study upon which it is based, in the words of its authors, was to "explore the roles of sea surface temperature coupling and land surface processes in producing the Sahel drought in CGCMs [coupled general circulation models] that participated in the twentieth-century coupled climate simulations of the Intergovernmental Panel on Climate Change [IPCC] Assessment Report 4." In the study of Lau *et al.*, these nineteen CGCMs were "driven by combinations of realistic prescribed external forcing, including anthropogenic increase in greenhouse gases and sulfate aerosols, long-term variation in solar radiation, and volcanic eruptions." This work revealed, according to Lau *et al.*, that "only eight models produce a reasonable Sahel drought signal, seven models produce excessive rainfall over [the] Sahel during the observed drought period, and four models show no significant deviation from normal." In addition, they report that "even the model with the highest skill for the Sahel drought could only simulate the increasing trend of severe drought events but not the magnitude, nor the beginning time and duration of the events." Consequently, since *all nineteen* of the CGCMs that were used in preparing the IPCC's Fourth Assessment Report were unable to adequately simulate the basic characteristics of what Lau *et al.* call one of the past century's "most pronounced signals of climate change," this *failure* of what they call an "ideal test" for evaluating the models' abilities to accurately simulate "long-term drought" and "coupled atmosphere-ocean-land processes and their interactions" would almost *mandate* that it would be unwise to rely on any of the models' output as a guide to the future, especially in light of the fact that even though the models were "driven by combinations of realistic prescribed external forcing," they *still* could not properly simulate even the *recent* past.

Leaving climate models behind, then, we turn our attention to instrumental and proxy drought records to see what they reveal about the propensity for rising temperatures to alter drought characteristics in different parts of Africa.

In a review of information pertaining to the past two centuries, Nicholson (2001) reports there has been "a long-term reduction in rainfall in the semi-arid regions of West Africa" that has been "on the order of 20 to 40% in parts of the Sahel." Describing the phenomenon as "three decades of protracted aridity," she reports that "nearly all of Africa has been affected ... particularly since the 1980s." Nevertheless, Nicholson says that "rainfall conditions over Africa during the last 2 to 3 decades are *not unprecedented* [our italics]," and that "a similar dry episode prevailed during most of the first half of the 19th century," when much of the planet was still experiencing Little Ice Age conditions.

More recently, Therrell *et al.* (2006) developed what they describe as "the first tree-ring reconstruction of rainfall in tropical Africa using a 200-year regional chronology based on samples of *Pterocarpus angolensis* [a deciduous tropical hardwood known locally as Mukwa] from Zimbabwe." This project revealed that "a decadal-scale drought reconstructed from 1882 to 1896 matches the most severe sustained drought during the instrumental period (1989-1995)," and that "an even more severe drought is indicated from 1859 to 1868 in both the tree-ring and documentary data." They report, for example, that the year 1860 (which was the most droughty year of the entire period), was described in a contemporary account from Botswana (where part of their tree-ring chronology originated) as "a season of 'severe and universal drought' with 'food of every description' being 'exceedingly scarce' and the losses of cattle being 'very severe' (Nash and Endfield, 2002)." At the other end of the moisture spectrum, Therrell *et al.* report that "a 6-year wet period at the turn of the nineteenth century (1897-1902) exceeds any wet episode during the instrumental era." Consequently, for a large part of central southern Africa, it is clear that the supposedly unprecedented global warming of the 20th century did *not* result in an intensification of either extreme dry or wet periods. If anything, just the *opposite* appears to have occurred.

Looking further back in time, Verschuren *et al.* (2000) developed a decadal-scale history of rainfall and drought in equatorial east Africa for the past *thousand* years, based on level and salinity fluctuations of a small crater-lake in Kenya that were derived from diatom and midge assemblages retrieved from the lake's sediments. Once again, they found that the Little Ice Age was generally wetter than the Modern Warm Period; but they identified three intervals of prolonged dryness within the Little Ice Age (1390-1420, 1560-1625, and 1760-1840), and of these "episodes of persistent aridity," as they refer to them, *all* were determined to have been "more severe than any recorded drought of the twentieth century."

Probing some 1500 years into the past was the study of Holmes *et al.* (1997), who wrote that since the late 1960s, the African Sahel had experienced "one of the most persistent droughts recorded by the entire global meteorological record." However, in a high-resolution study of a sediment sequence extracted from an oasis in the Manga Grasslands of northeast Nigeria, they too determined that "the present drought is not unique and that drought has recurred on a centennial to interdecadal timescale during the last 1500 years."

Last of all, and going back in time almost 5500 years, Russell and Johnson (2005) analyzed sediment cores that had been retrieved from Lake Edward - the smallest of the great rift lakes of East Africa, located on the border that separates Uganda and the Democratic Republic of the Congo - to derive a detailed precipitation history for that region. In doing so, they discovered that from the start of the record until about 1800 years ago, there was a long-term trend toward progressively more arid conditions, after which there followed what they term a "slight trend" toward wetter conditions that has persisted to the present. In addition, superimposed on these long-term trends were major droughts of "at least century-scale duration," centered at approximately 850, 1500, 2000 and 4100 years ago. Consequently, it would not be unnatural for another such drought to grip the region in the not-too-distant future; and if such were to happen, the world's climate alarmists would be quick to claim that the ongoing rise in the air's CO<sub>2</sub> content was responsible for it. Nevertheless, there would be no compelling reason to believe they were correct, for if such droughts have occurred before - with much *less* CO<sub>2</sub> in the air than there is currently - they can easily occur again, independent of whatever the air's CO<sub>2</sub> concentration might be doing.

In summation, real-world evidence from Africa suggests that the global warming of the past century or so has *not* led to either a greater frequency or severity of drought in that part of the world. Indeed, even the continent's worst drought in recorded meteorological history does not seem to have been any worse (in fact, it was actually much milder) than droughts that occurred periodically during much colder times. Hence, we see no reason to put any credence whatsoever in the claim that global warming leads to more frequent or severe droughts in Africa.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/d/droughtafrica.php>.

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### 5.1.2. Asia

Paulsen *et al.* (2003) employed high-resolution stalagmite records of  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  from Buddha Cave "to infer changes in climate in central China for the last 1270 years in terms of warmer, colder, wetter and drier conditions." Among the climatic episodes evident in their data were "those corresponding to the Medieval Warm Period, Little Ice Age and 20th-century warming, lending support to the global extent of these events." More specifically, their record begins in the depths of the Dark Ages Cold Period, which ends about AD 965 with the commencement of the Medieval Warm Period, which continues to approximately AD 1475, whereupon the Little Ice Age sets in and holds sway until about AD 1825, after which the warming responsible for the Modern Warm Period begins.

With respect to *hydrologic balance*, the last part of the Dark Ages Cold Period was characterized as wet. It, in turn, was followed by a dry, a wet, and another dry interval in the Medieval Warm Period, which was followed by a wet and a dry interval in the Little Ice Age, and finally a mostly wet but highly moisture-variable Modern Warm Period. Paulsen *et al.*'s data also reveal a number of other cycles superimposed on the major millennial-scale cycle of temperature and the centennial-scale cycle of moisture, most of which higher-frequency cycles they attribute to solar phenomena, concluding that the summer monsoon over eastern China, which brings the region much of its precipitation, may "be related to solar irradiance."

This study clearly indicates that earth's climate is determined by a conglomerate of cycles within cycles, all of which are essentially independent of the air's  $\text{CO}_2$  concentration; and it demonstrates that the multi-century warm and cold periods of the planet's millennial-scale oscillation of temperature may have both wetter and drier periods embedded within them. Consequently, it can be appreciated that warmth alone is not a sufficient condition for the concomitant occurrence of the dryness associated with drought.

Kalugin *et al.* (2005) worked with sediment cores from Lake Teletskoye in the Altai Mountains of Southern Siberia to produce a multi-proxy climate record spanning the past 800 years. This record revealed that the regional climate was relatively warm with high terrestrial productivity from AD 1210 to 1380. Thereafter, however, temperatures cooled and productivity dropped, reaching a broad minimum between 1660 and 1700, which interval, in their words,

"corresponds to the age range of the well-known Maunder Minimum (1645-1715)" and is "in agreement with the timing of the Little Ice Age in Europe (1560-1850)."

With respect to *moisture and precipitation*, Kalugin *et al.* state that the period between 1210 and 1480 was more humid than that of today, while the period between 1480 and 1840 was more arid. In addition, they report three episodes of multi-year drought (1580-1600, 1665-1690 and 1785-1810), which findings are in agreement with other historical data and tree-ring records from the Mongolia-Altai region (Butvilovskii, 1993; Jacoby *et al.*, 1996; Panyushkina *et al.*, 2000). Consequently, this study proves problematic for the climate-alarmist claim that global warming will lead to more frequent and more severe droughts, as *all* of the major multi-year droughts detected in this study occurred during the *cool* phase of the 800-year record.

Touchan *et al.* (2003) developed two reconstructions of spring precipitation for southwestern Turkey from tree-ring width measurements, one of them (1776-1998) based on nine chronologies of *Cedrus libani*, *Juniperus excelsa*, *Pinus brutia* and *Pinus nigra*, and the other one (1339-1998) based on three chronologies of *Juniperus excelsa*. These records, according to them, "show clear evidence of multi-year to decadal variations in spring precipitation." Nevertheless, they report that "dry periods of 1-2 years were well distributed throughout the record" and that the same was largely true of similar wet periods. With respect to more extreme events, the period *preceding* the Industrial Revolution stood out. They note, for example, that "all of the wettest 5-year periods occurred prior to 1756." Likewise, the longest period of reconstructed spring drought was the four-year period 1476-79, while the single driest spring was 1746. Once again, therefore, we see that what climate alarmists describe as the most dramatic warming of the past two millennia (that associated with the Industrial Revolution and its aftermath) produced no distinctive changes in the nature of drought in yet another part of Asia.

Cluis and Laberge (2001) analyzed streamflow records stored in the databank of the Global Runoff Data Center at the Federal Institute of Hydrology in Koblenz (Germany) to see if there were any changes in Asian river runoff of the type predicted by the IPCC to lead to more frequent and more severe drought. This study was based on the streamflow histories of 78 rivers said to be "geographically distributed throughout the whole Asia-Pacific region." The mean start and end dates of these series were  $1936 \pm 5$  years and  $1988 \pm 1$  year, respectively, representing an approximate half-century time span. In the case of the annual *minimum* discharges of these rivers, which are the ones associated with drought, 53% of them were unchanged over the period of the study; and where there were trends, 62% of them were upward, indicative of a growing likelihood of both less frequent and less severe drought.

Ducic (2005) analyzed observed and reconstructed discharge rates of the Danube River near Orsova, Serbia, over the period 1731-1990, finding that the lowest 5-year discharge value in the pre-instrumental era (period of occurrence: 1831-1835) was practically equal to the lowest 5-year discharge value in the instrumental era (period of occurrence: 1946-1950), and that the driest decade of the entire 260-year period was 1831-1840. What is more, the discharge rate for the last decade of the record (1981-1990), which prior researchers had claimed was

anthropogenically-influenced, was found to be "completely inside the limits of the whole series," in Ducic's words, and only slightly (0.7%) less than the 260-year mean. As a result, Ducic concluded that "modern discharge fluctuations do not point to [a] dominant anthropogenic influence." In fact, Ducic's correlative analysis suggests that the detected cyclicity in the record could "point to the domination of the influence of solar activity."

Jiang *et al.* (2005) analyzed historical documents to produce a time series of flood and drought occurrences in eastern China's Yangtze Delta since AD 1000. Their work revealed that alternating wet and dry episodes occurred throughout this period; and the data demonstrate that droughts and floods usually occurred in the spring and autumn seasons *of the same year*, with the most rapid and strongest of these fluctuations occurring during the Little Ice Age (1500-1850), as opposed to the preceding Medieval Warm Period and the following Current Warm Period.

Davi *et al.* (2006) employed absolutely dated tree-ring-width chronologies from five sampling sites in west-central Mongolia -- all of them "in or near the Selenge River basin, the largest river in Mongolia" -- to develop a reconstruction of streamflow that extends from 1637 to 1997. Of the ten driest five-year periods of the 360-year record, only one occurred during the 20th century (and that just barely: 1901-1905, sixth driest of the ten extreme periods), while of the ten wettest five-year periods, only two occurred during the 20th century (1990-1994 and 1917-1921, the second and eighth wettest of the ten extreme periods, respectively). Consequently, as Davi *et al.* describe the situation, "there is much wider variation in the long-term tree-ring record than in the limited record of measured precipitation," such that over the course of the 20th century, which climate alarmists describe as having experienced a warming that was *unprecedented over the past two millennia*, extremes of both dryness and wetness were both less frequent and less severe.

Sinha *et al.* (2007) derived a nearly annually-resolved record of Indian summer monsoon (ISM) rainfall variations for the core monsoon region of India that stretches from AD 600 to 1500 based on a  $^{230}\text{Th}$ -dated stalagmite oxygen isotope record from Dandak Cave, which is located at 19°00'N, 82°00'E. This work revealed that "the short instrumental record of ISM underestimates the magnitude of monsoon rainfall variability," and they state that "nearly every major famine in India [over the period of their study] coincided with a period of reduced monsoon rainfall as reflected in the Dandak  $\delta^{18}\text{O}$  record," noting two particularly devastating famines that "occurred at the beginning of the Little Ice Age during the longest duration and most severe ISM weakening of [their] reconstruction." In addition, they state that "ISM reconstructions from Arabian Sea marine sediments (Agnihotri *et al.*, 2002; Gupta *et al.*, 2003; von Rad *et al.*, 1999), stalagmite  $\delta^{18}\text{O}$  records from Oman and Yemen (Burns *et al.*, 2002; Fleitmann *et al.*, 2007) and a pollen record from the western Himalaya (Phadtare and Pant, 2006) also indicate a weaker monsoon during the Little Ice Age and a relatively stronger monsoon during the Medieval Warm Period." As a result, the eight researchers note that "since the end of the Little Ice Age, ca 1850 AD, the human population in the Indian monsoon region has increased from about 200 million to over 1 billion," and that "a recurrence of weaker intervals of ISM comparable to those inferred in our record would have serious implications to human health and economic

sustainability in the region," which suggests that the Current Warm Period the earth is experiencing is something for which a sizable fraction of the planet's population should be very thankful.

Last of all, Zhang *et al.* (2008) developed flood and drought histories of the past thousand years in China's Yangtze Delta, based on "local chronicles, old and very comprehensive encyclopaedia, historic agricultural registers, and official weather reports," after which "continuous wavelet transform was applied to detect the periodicity and variability of the flood/drought series" -- which they describe as "a powerful way to characterize the frequency, the intensity, the time position, and the duration of variations in a climate data series" -- and, finally, the results of the entire set of operations were compared with two one-thousand-year temperature histories of the Tibetan Plateau: northeastern Tibet and southern Tibet.

As a result of this effort, Zhang *et al.* report that "during AD 1400-1700 [the coldest portion of their record, corresponding to much of the Little Ice Age], the proxy indicators showing the annual temperature experienced larger variability (larger standard deviation), and this time interval *exactly* [our italics] corresponds to the time when the higher and significant wavelet variance occurred." In contrast, they report that "during AD 1000-1400 [the warmest portion of their record, corresponding to much of the Medieval Warm Period], relatively stable changes of climatic changes reconstructed from proxy indicators in Tibet correspond to lower wavelet variance of flood/drought series in the Yangtze Delta region."

In conclusion, the preponderance of real-world evidence from Asia provides no support whatsoever for the claim that global warming leads to the occurrence of either more frequent or more severe droughts.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/d/droughtasia.php>.

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### 5.1.3. Europe

We begin with a study from Central Scandinavia that provides a multi-century perspective on the issue. In it, Linderholm and Chen (2005) derived a 500-year history of winter (September-April) precipitation from tree-ring data obtained within the Northern Boreal zone of the region. This chronology indicated that below average precipitation was observed during the periods 1504-1520, 1562-1625, 1648-1669, 1696-1731, 1852-1871 and 1893-1958, with the *lowest* values occurring at the *beginning of the record* and at the *beginning of the 17th century*. These results demonstrate that for this portion of the European continent, 20th-century global warming did *not* result in more frequent or more severe droughts.

Another five-century perspective on the issue was provided by Wilson *et al.* (2005), who used a regional curve standardization technique to develop a *summer* (March-August) precipitation chronology from living and historical ring-widths of trees in the Bavarian Forest region of southeast Germany for the period 1456-2001. This technique captured low frequency variations that indicated the region was substantially drier than the long-term average during the periods 1500-1560, 1610-1730 and 1810-1870, all of which intervals were much colder than the bulk of the 20th century. Hence, these results too fly in the face of climate-alarmist predictions.

A third study of interest concerns the Danube River in western Europe, where several researchers had studied the precipitation histories of adjacent regions and suggested that an anthropogenic signal was present in the latter decades of the 20th century, and that it was responsible for that period's supposedly drier conditions. Determined to investigate further, Ducic (2005) examined these claims by analyzing observed and reconstructed discharge rates of the river near Orsova, Serbia over the period 1731-1990. This work revealed that the lowest 5-year discharge value in the pre-instrumental era (1831-1835) was practically equal to the lowest 5-year discharge value in the instrumental era (1946-1950), and that *the driest decade of the entire 260-year period was 1831-1840*. What is more, the discharge rate for the last decade of the record (1981-1990), which prior researchers had claimed was anthropogenically-influenced, was found to be "completely inside the limits of the whole series," in Ducic's words, and only 0.7% less than the 260-year mean, leading to the conclusion that "modern discharge

fluctuations do not point to dominant anthropogenic influence." In fact, Ducic's correlative analysis suggests that the detected cyclicity in the record could "point to the domination of the influence of solar activity."

In much the same vein and noting that "the media often reflect the view that recent severe drought events are signs that the climate has in fact already changed owing to human impacts," Hisdal *et al.* (2001) examined pertinent data from many places in Europe. Specifically, they performed a series of statistical analyses on more than 600 daily streamflow records from the European Water Archive to examine trends in the severity, duration and frequency of drought over the following four time periods: 1962-1990, 1962-1995, 1930-1995, and 1911-1995. This work revealed, in their words, that "despite several reports on recent droughts in Europe, there is no clear indication that streamflow drought conditions in Europe have generally become more severe or frequent in the time periods studied." To the contrary, they report that "overall, the number of negative significant trends pointing towards decreasing drought deficit volumes or fewer drought events exceeded the number of positive significant trends (increasing drought deficit volumes or more drought events)."

In conclusion, it is clear from these several reports that the portrayal of increasing 20th-century warming-induced drought in Europe is *not* supported by real-world data, just as it is not supported by data from other continents.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/d/droughteurope.php>.

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## 5.1.4. North America

### 5.1.4.1. Canada

Knowledge of the past is extremely important when it comes to contemplating future climatic possibilities; for what's happened before can happen again. Hence, we here briefly review the

history of Canadian droughts with respect to how they varied over the past several centuries in response to changes in global air temperature. This exercise provides some idea of what we may expect to occur with Canadian droughts in the post-Little Ice Age world we call the Current Warm Period.

Gan (1998) performed several statistical tests on data sets pertaining to temperature, precipitation, spring snowmelt dates, streamflow, potential and actual evapotranspiration, and the duration, magnitude and severity of drought throughout the Canadian Prairie Provinces of Alberta, Saskatchewan and Manitoba. The results of these several tests suggest that the Prairies have become somewhat warmer and drier over the last four to five decades, although there are regional exceptions to this generality. After weighing all of the pertinent facts, however, Gan reports "there is no solid evidence to conclude that climatic warming, if it occurred, has caused the Prairie drought to become more severe," further noting, in contrast to most climate-alarmist claims, that "the evidence is insufficient to conclude that warmer climate will lead to more severe droughts in the Prairies."

Working in the same general area, Quiring and Papakyriakou (2005) used an agricultural drought index (Palmer's Z-index) to characterize the frequency, severity and spatial extent of June-July moisture anomalies for 43 crop districts from the agricultural region of the Canadian prairies over the period 1920-99. This work revealed that for the 80-year period of their study, the single most severe June-July drought on the Canadian prairies occurred in 1961, and that the next most severe droughts, in descending order of severity, occurred in 1988, 1936, 1929 and 1937, for little net overall trend. Simultaneously, however, they say there was an *upward* trend in *mean* June-July moisture conditions. In addition, they note that "reconstructed July moisture conditions for the Canadian prairies demonstrate that droughts during the 18th and 19th centuries were more persistent than those of the 20th century (Sauchyn and Skinner, 2001)."

In a subsequent study that covered an even longer span of time, St. George and Nielsen (2002) used "a ringwidth chronology developed from living, historical and subfossil bur oak in the Red River basin to reconstruct annual precipitation in southern Manitoba since AD 1409." And their findings? They say that "prior to the 20th century, southern Manitoba's climate was more extreme and variable, with prolonged intervals that were wetter and drier than any time following permanent Euro-Canadian settlement." Hence, it is clear that 20th-century warming, if anything, has led to more *stable* climatic conditions with *fewer* hydrologic extremes (floods and droughts) than was typical of prior Little Ice Age conditions. Consequently, St. George and Nielsen conclude that "climatic case studies in regional drought and flood planning based exclusively on experience during the 20th century may dramatically underestimate true worst-case scenarios." What is more, they indicate that "multidecadal fluctuations in regional hydroclimate have been remarkably coherent across the northeastern Great Plains during the last 600 years," and that "individual dry years in the Red River basin were usually associated with larger scale drought across much of the North American interior," which suggests that their results for the Red River basin are likely representative of this entire larger region.

Taking an even longer look back in time, Campbell (2002) analyzed the grain sizes of sediment cores obtained from Pine Lake, Alberta, Canada to derive a non-vegetation-based high-resolution record of climate variability over the past 4000 years. Throughout this record, periods of both increasing and decreasing moisture availability, as determined from grain size, were evident at decadal, centennial and millennial time scales, as was also found by Laird *et al.* (2003) in a study of diatom assemblages in sediment cores taken from three additional Canadian lakes. Over the most recent 150 years, however -- the last century of which climate alarmists typically characterize as having experienced "unprecedented" global warming -- the grain size of the Pine Lake study generally remained above the 4000-year average, indicative of relatively stable and *less* droughty conditions than the mean of the last four millennia.

In a somewhat different type of study in another part of the country, Carcaillet *et al.* (2001) developed high-resolution *charcoal* histories from laminated sediment cores extracted from three small kettle lakes located within the mixed-boreal and coniferous-boreal forest region of eastern Canada, after which they determined whether vegetation change or climate change was the primary determinant of the fire frequency variation they observed, comparing their fire history with hydro-climatic reconstructions derived from  $\delta^{18}\text{O}$  and lake-level data. Throughout the Climatic Optimum of the mid-Holocene, between about 7000 and 3000 years ago when it was significantly warmer than it is today, they found that "fire intervals were double those in the last 2000 years," meaning fires were only half as frequent throughout the earlier warmer period as they were during the subsequent cooler period. They also determined that "vegetation does not control the long-term fire regime in the boreal forest." Rather, they found that "climate appears to be the main process triggering fire." In addition, they report that "dendroecological studies show that both frequency and size of fire decreased during the 20th century in both west (e.g. Van Wagner, 1978; Johnson *et al.*, 1990; Larsen, 1997; Weir *et al.*, 2000) and east Canadian coniferous forests (e.g. Cwynar, 1997; Foster, 1983; Bergeron, 1991; Bergeron *et al.*, 2001), possibly due to a drop in drought frequency and an increase in long-term annual precipitation (Bergeron and Archambault, 1993)."

Also working in eastern Canada, Girardin *et al.* (2004) developed a 380-year reconstruction of the Canadian Drought Code (CDC, a daily numerical rating of the average moisture content of deep soil organic layers in boreal conifer stands that is used to monitor forest fire danger) for the month of July, based on 16 well replicated tree-ring chronologies from the Abitibi Plains of eastern Canada just below James Bay. Cross-continuous wavelet transformation analyses of these data, in their words, "indicated coherency in the 8-16 and 17-32-year per cycle oscillation bands between the CDC reconstruction and the Pacific Decadal Oscillation prior to 1850," while "following 1850, the coherency shifted toward the North Atlantic Oscillation." These results led them to suggest that "the end of [the] 'Little Ice Age' over the Abitibi Plains sector corresponded to a decrease in the North Pacific decadal forcing around the 1850s," and that "this event could have been followed by an inhibition of the Arctic air outflow and an incursion of more humid air masses from the subtropical Atlantic climate sector," which may have helped reduce fire frequency and drought severity. In this regard, they note that several other paleoclimate and ecological studies have suggested that "climate in eastern Canada started to change with the end of the 'Little Ice Age' (~1850)," citing the works of Tardif and Bergeron

(1997, 1999), Bergeron (1998, 2000) and Bergeron *et al.* (2001), while further noting that Bergeron and Archambault (1993) and Hofgaard *et al.* (1999) have "speculated that the poleward retreat of the Arctic air mass starting at the end of the 'Little Ice Age' contributed to the incursion of moister air masses in eastern Canada."

Moving back towards the west, Wolfe *et al.* (2005) conducted a multi-proxy hydro-ecological analysis of Spruce Island Lake in the northern Peace sector of the Peace-Athabasca Delta in northern Alberta. Their research revealed that hydro-ecological conditions in that region varied substantially over the past 300 years, especially in terms of multi-decadal dry and wet periods. More specifically, they found that (1) recent drying in the region was not the product of Peace River flow regulation that began in 1968, but rather the product of an extended drying period that was initiated in the early to mid-1900s, (2) the multi-proxy hydro-ecological variables they analyzed were well correlated with other reconstructed records of natural climate variability, and (3) hydro-ecological conditions after 1968 *have remained well within the broad range of natural variability observed over the past 300 years*, with the earlier portion of the record actually depicting "markedly wetter and drier conditions compared to recent decades."

Moving all the way to the Pacific coast of North America (Heal Lake near the city of Victoria on Canada's Vancouver Island), Zhang and Hebda (2005) conducted dendroclimatological analyses of 121 well-preserved subfossil logs discovered at the bottom of the lake plus 29 Douglas-fir trees growing nearby that led to the development of an ~ 4,000-year chronology exhibiting sensitivity to spring precipitation. In doing so, they found that "the magnitude and duration of climatic variability during the past 4000 years are not well represented by the variation in the brief modern period." As an example of this fact, they note that spring droughts represented by ring-width departures exceeding two standard deviations below the mean in at least five consecutive years occurred in the late AD 1840s and mid 1460s, as well as the mid 1860s BC, and were more severe than any drought of the 20th century. In addition, the most persistent drought occurred during the 120-year period between about AD 1440 and 1560. Other severe droughts of multi-decadal duration occurred in the mid AD 760s-800s, the 540s-560s, the 150s-late 190s and around 800 BC. Wavelet analyses of the tree-ring chronology also revealed a host of natural oscillations on timescales of years to centuries, demonstrating that the 20th century was in no way unusual in this regard, as there were many times throughout the prior 4000 years when it was both wetter and drier than it was during the last century of the past millennium.

In view of these several similar findings across a wide and varying geographic area, it would appear that most of Canada has experienced significantly less drought as it and the rest of the world have emerged from the cold conditions of the Little Ice Age and begun basking in the higher temperatures of the Current Warm Period.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/d/droughtcanada.php>.

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#### 5.1.4.2. Mexico

Stahle *et al.* (2000) developed a long-term history of drought over much of North America from reconstructions of the Palmer Drought Severity Index, based on analyses of many lengthy tree-ring records. This history reveals the occurrence of a 16th-century drought in Mexico that persisted from the 1540s to the 1580s. Writing of this anomalous period of much reduced precipitation, they say that "the 'megadrought' of the 16th century far exceeded any drought of the 20th century," when climate alarmists claim the planet experienced a level of warmth that was *unprecedented over the past two millennia* and should therefore, according to their reasoning, have been host to the most extreme lack of moisture of the studied period.

Diaz *et al.* (2002) constructed a history of winter-spring (November-April) precipitation -- which accounts for one-third of the yearly total -- for the Mexican state of Chihuahua for the period 1647-1992, based on earlywood width chronologies of over 300 Douglas fir trees growing at four locations along the western and southern borders of Chihuahua and at two locations in the United States just above Chihuahua's northeast border. On the basis of these reconstructions, they correctly note that "three of the 5 worst winter-spring drought years in the past three-and-a-half centuries are estimated to have occurred during the 20th century." Although this observation tends to make the 20th century look highly anomalous in this regard, it is not; for two of those three worst drought years occurred during a period of average to slightly-above-average precipitation.

Diaz *et al.* also correctly note that "the longest drought indicated by the smoothed reconstruction lasted 17 years (1948-1964)," which is again correct and seemingly indicative of abnormally dry conditions during the 20th century. However, for several of the 17 years of that below-normal-precipitation interval, precipitation values were only *slightly* below normal. For all practical purposes, therefore, there were four very similar dry periods interspersed throughout the preceding two and a half centuries: one in the late 1850s and early 1860s, one in the late 1790s and early 1800s, one in the late 1720s and early 1730s, and one in the late 1660s and early 1670s.

With respect to the 20th century alone, there was also a long period of *high* winter-spring precipitation that stretched from 1905 to 1932; and following the major drought of the 1950s, precipitation remained at or just slightly above normal for the remainder of the record. Finally, with respect to the entire 346 years, there is no long-term trend in the data, nor is there any evidence of any sustained departure from that trend over the course of the 20th century, indicating that neither 20th century anthropogenic CO<sub>2</sub> emissions nor 20th century warming have significantly impacted rainfall in the Mexican state of Chihuahua.

Cleaveland *et al.* (2003) constructed a winter-spring (November-March) precipitation history for the period 1386-1993 for Durango, Mexico, based on earlywood width chronologies of Douglas-fir tree rings collected at two sites in the Sierra Madre Occidental. They report that this record "shows droughts of greater magnitude and longer duration than the worst historical drought that occurred in the 1950s and 1960s." These earlier dramatic droughts include the long dry spell of the 1850s-1860s and what they call the *megadrought* of the mid- to late-16th century.



Hence, their work clearly demonstrates that the worst droughts of the past 600 years did *not* occur during the period of greatest warmth, as the world's climate alarmists are fond of saying they should. Instead, they occurred during the Little Ice Age, which was perhaps *the coldest period of the current interglacial*.

Investigating the same approximate time period, Hodell *et al.* (2005b) analyzed a 5.1-m sediment core they retrieved from Aguada X'caamal, a small sinkhole lake in northwest Yucatan, Mexico, finding that an important hydrologic change occurred there during the 15th century AD, as documented by the appearance of *A. beccarii* in the sediment profile, a decline in the abundance of charophytes, and an increase in the  $\delta^{18}\text{O}$  of gastropods and ostracods. In addition, they report that "the salinity and  $^{18}\text{O}$  content of the lake water increased as a result of reduced precipitation and/or increased evaporation in the mid- to late 1500s." These several changes, as well as many others they cite, were, as they describe it, "part of a larger pattern of oceanic and atmospheric change associated with the Little Ice Age that included cooling throughout the subtropical gyre (Lund and Curry, 2004)." Their assessment of the situation was that the "climate became drier on the Yucatan Peninsula in the 15th century AD near the onset of the Little Ice Age," as is also suggested by Maya and Aztec chronicles that "contain references to cold, drought and famine in the period AD 1441-1460."

Going back even further in time, Hodell *et al.* (1995) had provided evidence for a protracted drought during the Terminal Classic Period of Mayan civilization (AD 800-1000), based on their analysis of a single sediment core retrieved in 1993 from Lake Chichanacanab in the center of the northern Yucatan Peninsula of Mexico. Subsequently, based on two additional sediment cores retrieved from the same location in 2000, Hodell *et al.* (2001) determined that the massive drought likely occurred in two distinct phases (750-875 and 1000-1075). Reconstructing the climatic history of the region over the past 2600 years and applying spectral analysis to the data also revealed a significant recurrent drought periodicity of 208 years that matched well with a cosmic ray-produced  $^{14}\text{C}$  record preserved in tree rings, which is believed to reflect variations in solar activity; and because of the good correspondence between the two data sets, they concluded that "a significant component of century-scale variability in Yucatan droughts is explained by solar forcing."

In a still-later study, Hodell *et al.* (2005a) returned to Lake Chichanacanab in March of 2004 and retrieved a number of additional sediment cores in some of the deeper parts in the lake, with multiple cores being taken from its deepest point, from which depth profiles of bulk density were obtained by means of gamma-ray attenuation, as were profiles of reflected red, green and blue light via a digital color line-scan camera. As they describe their findings, "the data reveal in great detail the climatic events that comprised the Terminal Classic Drought and coincided with the demise of Classic Maya civilization." In this regard, they again report that "the Terminal Classic Drought was not a single, two-century-long megadrought, but rather consisted of a series of dry events separated by intervening periods of relatively moister conditions," and that it "included an early phase (ca 770-870) and late phase (ca 920-1100)." Last of all, they say that "the bipartite drought history inferred from Chichanacanab is supported by oxygen isotope records from nearby Punta Laguna," and that "the general pattern is also consistent with

findings from the Cariaco Basin off northern Venezuela (Haug *et al.*, 2003), suggesting that the Terminal Classic Drought was a widespread phenomenon and not limited to north-central Yucatan."

Concurrent with the study of Hodell *et al.* (2005a), Almeida-Lenero *et al.* (2005) analyzed pollen profiles derived from sediment cores retrieved from Lake Zempoala and nearby Lake Quila in the central Mexican highlands about 65 km southwest of Mexico City, determining that it was generally more humid than at present in the central Mexican highlands during the mid-Holocene. Thereafter, however, there was a gradual drying of the climate; and their data from Lake Zempoala indicate that "the interval from 1300 to 1100 cal yr BP was driest and represents an extreme since the mid-Holocene," noting further that this interval of 200 years "coincides with the collapse of the Maya civilization." Likewise, they report that their data from Lake Quila are also "indicative of the most arid period reported during the middle to late Holocene from c. 1300 to 1100 cal yr BP." In addition, they note that "climatic aridity during this time was also noted by Metcalfe *et al.* (1991) for the Lerma Basin [central Mexico]," that "dry climatic conditions were also reported from Lake Patzcuaro, central Mexico by Watts and Bradbury (1982)," and that "dry conditions were also reported for [Mexico's] Zacapu Basin (Metcalfe, 1995) and for [Mexico's] Yucatan Peninsula (Curtis *et al.*, 1996, 1998; Hodell *et al.*, 1995, 2001)."

Based on the many results described above, it is evident that throughout much of Mexico some of the driest conditions and worst droughts of the Late Holocene occurred during the Little Ice Age and the latter part of the Dark Ages Cold Period. These observations do much to discredit the model-based claim that droughts will only get worse as air temperatures rise, especially when it is realized that *all* of the Mexican droughts of the 20th century were much milder than many of the droughts that occurred during much colder centuries.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/d/droughtmexico.php>.

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### 5.1.4.3. United States

#### 5.1.4.3.1. CENTRAL

Starting at the U.S.-Canadian border and working our way south, we begin with the study of Fritz *et al.* (2000), who utilized data derived from sediment cores retrieved from three North Dakota lakes to reconstruct a 2000-year history of drought in this portion of the Northern Great Plains. This work suggested, in their words, "that droughts equal or greater in magnitude to those of the Dust Bowl period were a *common occurrence* [our italics] during the last 2000 years." Hence, their real-world data demonstrate that, if anything, the modest warming that released the planet from the global chill of the Little Ice Age may have initiated a period of *less* frequent and severe droughts.

Also working in the Northern Great Plains, but extending down into South Dakota, Shapley *et al.* (2005) developed a 1000-year hydroclimate reconstruction from local bur oak tree-ring records and various lake sediment cores. Based on this record, they determined that *prior to 1800*, "droughts tended towards *greater persistence* [our italics] than during the past two centuries," suggesting that droughts of the region became shorter-lived as opposed to longer-lasting as the earth gradually recovered from the cold temperatures of the Little Ice Age.

The above observations are significant because the United States' Northern Great Plains is an important agricultural region, providing a significant source of grain for both local and international consumption. However, the region is susceptible to periodic extreme droughts that tend to persist longer than those in any other part of the country (Karl *et al.*, 1987; Soule, 1992); and because of this fact, Laird *et al.* (1998) examined the region's historical record of drought in an attempt to establish a baseline of natural drought variability that could help in attempts to determine if current and future droughts might be anthropogenically influenced.

Working with a high-resolution sediment core obtained from Moon Lake, North Dakota, which provided a sub-decadal record of salinity (drought) over the past 2300 years, they discovered that the U.S. Northern Great Plains were relatively wet during the final 750 years of this period. In fact, throughout the 1550 prior years, Laird *et al.* determined that "recurring severe droughts were more the norm," and that they were "of much greater intensity and duration than any in the 20th century," including the great Dust Bowl event of the 1930s. Consequently, and in light of their finding that there were, as they put it, "no modern equivalents" to Northern Great Plains droughts experienced prior to AD 1200, it would appear that 20th-century global warming has had absolutely no effect on drought conditions in this part of the world.

Continuing our southward trek, we encounter the work of Forman *et al.* (2005), who note that "periods of dune reactivation reflect sustained moisture deficits for years to decades and reflect broader environmental change with diminished surface- and ground-water resources," which observation prompted them to focus on "the largest dune system in North America, the Nebraska Sand Hills," where they utilized "recent advances in optically stimulated luminescence dating (Murray and Wintle, 2000) to improve chronologic control on the timing of dune reactivation," while linking landscape response to drought over the past 1500 years to tree-ring records of aridity.

In pursuing their goal, Forman *et al.* identified six major aeolian depositional events in the past 1500 years, all but one of which (the 1930s "Dust Bowl" drought) occurred prior to the 20th century. Moving backwards in time from the Dust Bowl, the next three major events occurred during the depths of the Little Ice Age, the next one near the Little Ice Age's inception, and the earliest one near the end of the Dark Ages Cold Period. As for how the earlier droughts compare with those of the past century, the researchers say the 1930s drought (the 20th century's worst depositional event) was *less severe than the others*, especially the one that has come to be known as the 16th-century *megadrought*. Forman *et al.* thus conclude that the aeolian landforms they studied "are clear indicators of climate variability *beyond twentieth century norms* [our italics], and signify droughts of *greater severity and persistence* [our italics] than thus far instrumentally recorded." Consequently, their study reveals that post-Little Ice Age warming - which climate alarmists claim to be *unprecedented over the past two millennia* - has *not* produced similarly unprecedented droughts. In fact, in the U.S. Great Plains the increase in temperature appears to have done just the *opposite*.

In a study that covered the entirety of the U.S. Great Plains, Daniels and Knox (2005) analyzed the alluvial stratigraphic evidence for an episode of major channel incision in tributaries of the upper Republican River that occurred between 1100 and 800 years ago, after which they compared their findings with proxy drought records from 28 other locations throughout the Great Plains and surrounding regions. This work revealed that channel incision in the Republican River between about AD 900 and 1200 was well correlated with a multi-centennial episode of widespread drought, which in the words of Daniels and Knox, "coincides with the globally recognized Medieval Warm Period." Of great interest, however, is the fact that modern 20th-century warming has *not* led to a repeat of those widespread drought conditions.

Working in pretty much the same area some seven years earlier, Woodhouse and Overpeck (1998) reviewed what we know about the frequency and severity of drought in the central United States over the last two thousand years based upon empirical evidence of drought from various proxy indicators. Their study indicated the presence of *numerous* "multidecadal- to century-scale droughts," leading them to conclude that "twentieth-century droughts are not representative of the full range of drought variability that has occurred over the last 2000 years." In addition, they noted that the 20th century was characterized by droughts of "moderate severity and comparatively short duration, relative to the full range of past drought variability."

With respect to the *causes* of drought, Woodhouse and Overpeck suggest a number of different possibilities that either directly or indirectly induce changes in atmospheric circulation and moisture transport. However, they caution that "the causes of droughts with durations of years (i.e., the 1930s) to decades or centuries (i.e., paleodroughts) are not well understood." Hence, they conclude that "the full range of past natural drought variability, deduced from a comprehensive review of the paleoclimatic literature, suggests that droughts more severe than those of the 1930s and 1950s are likely to occur in the future," and, we might add, irrespective of whatever the air's CO<sub>2</sub> concentration or temperature might be doing in future years.

In concluding this mini-review, we focus on the work of Mauget (2004), who looked for what he called "initial clues" to the commencement of the great drying of the U.S. Heartland that had been predicted to occur in response to CO<sub>2</sub>-induced global warming by Manabe and Wetherald (1987), Rind *et al.* (1990), Rosenzweig and Hillel (1993), and Manabe *et al.* (2004), which Mauget rightly reasoned would be apparent in the observational streamflow record of the region. In this endeavor, he thus employed data he obtained from the archives of the U.S. Geological Survey's Hydro-Climatic Data Network, which come from 42 stations covering the central third of the United States that stretch from the Canadian border on the north to the Gulf of Mexico on the south, with the most dense coverage being found within the U.S. Corn Belt.

So what did Mauget learn?

He reports finding "an overall pattern of low flow periods before 1972, and high flow periods occurring over time windows beginning after 1969." Of the 42 stations' high flow periods, he says that "34 occur during 1969-1998, with 25 of those periods ending in either 1997 or 1998," and that "of those 25 stations 21 are situated in the key agricultural region known as the Corn Belt." He also reports that "among most of the stations in the western portions of the Corn Belt during the 1980s and 1990s there is an unprecedented tendency toward extended periods of daily high flow conditions, which lead to marked increases in the mean annual frequency of hydrological surplus conditions relative to previous years." What is more, he notes that "in 15 of the 18 Corn Belt gage stations considered here at daily resolution, a more than 50% reduction in the mean annual incidence of hydrological drought conditions is evident during those periods." Last of all, Mauget reports that "the gage station associated with the largest watershed area - the Mississippi at Vicksburg - shows more than a doubling of the mean annual frequency of hydrological surplus days during its 1973-1998 high flow period relative to previous years, and more than a 50% reduction in the mean annual incidence of hydrological drought condition."

In summarizing his findings, Mauget states that the overall pattern of climate variation "is that of a reduced tendency to hydrological drought and an increased incidence of hydrological surplus over the Corn Belt and most of the Mississippi River basin during the closing decades of the 20th century," noting further that "some of the most striking evidence of a transition to wetter conditions in the streamflow analyses is found among streams and rivers situated along the Corn Belt's climatologically drier western edge."

Do these findings represent the early stages of *real-world* climate change? Mauget states that the streamflow data do indeed "suggest a fundamental climate shift, as the most significant incidence of high ranked annual flow was found over relatively long time scales at the end of the data record." And that shift, as we hardly need to emphasize, is *away from* the droughty conditions long predicted to result from CO<sub>2</sub>-induced global warming in this important agricultural region of the United States.

What more can be said? Climate alarmists have it all wrong, as do the models upon which they base their errant claims. Modern global warming, if anything, has tended to *lessen* drought conditions throughout the central third of the United States.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/d/droughtusacentral.php>.

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#### 5.1.4.3.2. EASTERN

Cronin *et al.* (2000) studied the salinity gradient across sediment cores from Chesapeake Bay, the largest estuary in the United States, in an effort to examine precipitation variability in the surrounding watershed over the past millennium. Their work revealed the existence of a *high degree of decadal and multidecadal variability* between wet and dry conditions throughout the 1000-year record, where regional precipitation totals fluctuated by 25 to 30%, often in "extremely rapid [shifts] occurring over about a decade." In addition, precipitation over the last two centuries of the record was found to be generally *greater* than it was during the previous eight centuries, with the exception of the Medieval Warm Period (AD 1250-1350) when the [local] climate was found to be "extremely wet." Equally significant was the ten researchers' finding that the region had experienced several "mega-droughts" that had lasted for 60 to 70 years, several of which they judged to have been "more severe than twentieth century droughts."

Building upon the work of Cronin *et al.* were Willard *et al.* (2003), who examined the last 2300 years of the Holocene record of Chesapeake Bay and the adjacent terrestrial ecosystem "through the study of fossil dinoflagellate cysts and pollen from sediment cores." In doing so, they found that "several dry periods ranging from decades to centuries in duration are evident in Chesapeake Bay records." The first of these periods of lower-than-average precipitation (200 BC-AD 300) occurred during the latter part of the Roman Warm Period, while the next such period (~AD 800-1200), according to Willard *et al.*, "corresponds to the 'Medieval Warm Period'." In addition, they identified several decadal-scale dry intervals that spanned the years AD 1320-1400 and 1525-1650.

In discussing their findings, Willard *et al.* note that "mid-Atlantic dry periods generally correspond to central and southwestern USA 'megadroughts', which are described by Woodhouse and Overpeck (1998) as major droughts of decadal or more duration that probably exceeded twentieth-century droughts in severity." Emphasizing this important point, they additionally indicate that "droughts in the late sixteenth century that lasted several decades, and those in the 'Medieval Warm Period' and between ~AD 50 and AD 350 spanning a century or more have been indicated by Great Plains tree-ring (Stahle *et al.*, 1985; Stahle and Cleaveland, 1994), lacustrine diatom and ostracode (Fritz *et al.*, 2000; Laird *et al.*, 1996a, 1996b) and detrital clastic records (Dean, 1997)." Hence, their work in the eastern United States, together with the work of other researchers in still other parts of the country,



demonstrates that 20th-century global warming has *not* led to the occurrence of unusually strong wet or dry periods, contradicting climate-alarmist claims that warming will exacerbate extreme climate anomalies.

In concluding our brief review of this issue as it pertains to the eastern United States, we note that Quiring (2004) introduced his study of the subject by describing the drought of 2001-2002, which by June of the latter year had produced anomalously dry conditions along most of the east coast of the country, including severe drought conditions from New Jersey to northern Florida that forced 13 states to ration water. Shortly after the drought began to subside in October of 2002, however, moist conditions returned and persisted for about a year, producing the wettest growing-season of the instrumental record. These observations, in Quiring's words, "raise some interesting questions," including the one we are considering here. As he phrased the call to inquiry, "are moisture conditions in this region becoming more variable?"

Using an 800-year tree-ring-based reconstruction of the Palmer Hydrological Drought Index to address this question, Quiring documented the frequency, severity and duration of growing-season moisture anomalies in the southern mid-Atlantic region of the United States. Among other things, this work revealed, in Quiring's words, that "conditions during the 18th century were much wetter than they are today, and the droughts that occurred during the 16th century tended to be both longer and more severe." Hence, he concluded that "the recent growing-season moisture anomalies that occurred during 2002 and 2003 can only be considered rare events if they are evaluated with respect to the relatively short instrumental record (1895-2003)," for when compared to the 800-year reconstructed record, he notes that "neither of these events is particularly unusual." In addition, Quiring reports that "although climate models predict decreases in summer precipitation and significant increases in the frequency and duration of extreme droughts, the data indicate that growing-season moisture conditions during the 20th century (and even the last 19 years) appear to be near normal (well within the range of natural climate variability) when compared to the 800-year record."

In conclusion, it is clear that claims of droughts becoming more extreme and erratic in response to global warming are totally incorrect, or so, at least, is the story told by palaeoclimate data from the United States, the eastern portion of which has been highlighted in this summary.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/d/droughtusaeast.php>.

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#### 5.1.4.3.3. WESTERN

Climate alarmists vehemently contend that rising global temperatures lead to more severe and longer-lasting droughts on the basis of simulations of global climate change produced by mathematical models that are primarily driven by increases in the atmosphere's CO<sub>2</sub> concentration. In this section, we evaluate that strident claim for the western United States. This we do via a discussion of the findings of various scientific papers that scrutinize the contention through the discerning microscope of real-world proxy climate data. We begin our journey of inquiry just below Canada, in the U.S. Pacific Northwest, from whence we gradually wend our way to the U.S./Mexico border.

Knapp *et al.* (2002) created a 500-year history of severe single-year Pacific Northwest droughts from a study of eighteen western juniper tree-ring chronologies that they used to identify what they call extreme Climatic Pointer Years or CPYs, which are indicative of severe single-year droughts. As they describe it, this procedure revealed that "widespread and extreme CPYs were concentrated in the 16th and early part of the 17th centuries," while "both the 18th and 19th centuries were largely characterized by a paucity of drought events that were severe and widespread." Thereafter, however, they say that "CPYs became more numerous during the 20th century," although the number of 20th century extreme CPYs (26) was still *substantially* less than the mean of the number of 16th and 17th century extreme CPYs (38), when the planet

was considerably colder. Hence, the data of this study fail to support the climate-alarmist claim that global warming increases the frequency of severe droughts.

Gedalof *et al.* (2004) used a network of 32 drought-sensitive tree-ring chronologies to reconstruct mean water-year flow on the Columbia River at The Dales in Oregon since 1750. This study of the second largest drainage basin in the United States is stated by them to have been done "for the purpose of assessing the representativeness of recent observations, especially with respect to low frequency changes and extreme events." When finished, it revealed, in their words, that "persistent low flows during the 1840s were probably the most severe of the past 250 years," and that "the drought of the 1930s is probably the second most severe."

More recent droughts, in the words of the researchers, "have led to conflicts among uses (e.g., hydroelectric production versus protecting salmon runs), increased costs to end users (notably municipal power users), and in some cases the total loss of access to water (in particular junior water rights holders in the agricultural sector)." Nevertheless, they say that "these recent droughts were not exceptional in the context of the last 250 years and were of shorter duration than many past events." In fact, they say that "the period from 1950 to 1987 is anomalous in the context of this record for having no notable multiyear drought events," once again demonstrating the fact that Pacific Northwest droughts have not become more severe or long-lasting as temperatures have risen over the course of the 20th century.

Working in the Bighorn Basin of north-central Wyoming and south-central Montana, Gray *et al.* (2004) used cores and cross sections from 79 Douglas fir and limber pine trees at four different sites to develop a proxy for annual precipitation spanning the period AD 1260-1998. This reconstruction, in their words, "exhibits considerable nonstationarity, and the instrumental era (post-1900) in particular fails to capture the full range of precipitation variability experienced in the past ~750 years." More specifically, they say that "both single-year and decadal-scale dry events were more severe before 1900," and that "dry spells in the late thirteenth and sixteenth centuries surpass both [the] magnitude and duration of any droughts in the Bighorn Basin after 1900." In fact, they say that "single- and multi-year droughts *regularly* [our italics] surpassed the severity and magnitude of the 'worst-case scenarios' presented by the 1930s and 1950s droughts." Hence, if 20th-century global warming had any effect at all on Bighorn Basin precipitation, it was to make it *less* extreme rather than more extreme, in striking contradiction of the fervent claims to the contrary of the world's climate alarmists.

Moving further south, Benson *et al.* (2002) developed continuous high-resolution  $\delta^{18}\text{O}$  records from cored sediments of Pyramid Lake, Nevada, which they used to help construct a 7600-year history of droughts throughout the surrounding region. Oscillations in the hydrologic balance that were evident in this record occurred, on average, about every 150 years, but with significant variability. Over the most recent 2740 years, for example, intervals between droughts ranged from 80 to 230 years; while drought *durations* ranged from 20 to 100 years, with some of the larger ones forcing mass migrations of indigenous peoples from lands that

could no longer support them. In contrast, historical droughts typically have lasted *less than a decade*.

In another study based on sediment cores extracted from Pyramid Lake, Nevada, Mensing *et al.* (2004) analyzed pollen and algal microfossils deposited there over the prior 7630 years that allowed them to infer the hydrologic history of the area over that time period. Their results indicated that "sometime after 3430 but before 2750 cal yr B.P., climate became cool and wet," but, paradoxically, that "the past 2500 yr have been marked by recurring persistent droughts." The longest of these droughts, according to them, "occurred between 2500 and 2000 cal yr B.P.," while others occurred "between 1500 and 1250, 800 and 725, and 600 and 450 cal yr B.P.," with none recorded in more recent warmer times.

The researchers also note that "the timing and magnitude of droughts identified in the pollen record compares favorably with previously published  $\delta^{18}\text{O}$  data from Pyramid Lake" and with "the ages of submerged rooted stumps in the Eastern Sierra Nevada and woodrat midden data from central Nevada." Last of all, noting that Bond *et al.* (2001) "found that over the past 12,000 yr, decreases in [North Atlantic] drift ice abundance corresponded to increased solar output," they report that when they "compared the pollen record of droughts from Pyramid Lake with the stacked petrologic record of North Atlantic drift ice ... nearly every occurrence of a shift from ice maxima (reduced solar output) to ice minima (increased solar output) corresponded with a period of prolonged drought in the Pyramid Lake record." As a result, Mensing *et al.* concluded that "changes in solar irradiance may be a possible mechanism influencing century-scale drought in the western Great Basin [of the United States]." Indeed, it would appear from their analysis that variable solar activity may well be the *major* factor in determining the hydrologic condition of the region.

Only a state away, Gray *et al.* (2004) used samples from 107 piñon pines at four different sites to develop a proxy record of annual precipitation spanning the AD 1226- 2001 interval for the Uinta Basin watershed of northeastern Utah. This effort revealed, in their words, that "single-year dry events before the instrumental period tended to be more severe than those after 1900," and that decadal-scale dry events were longer and more severe prior to 1900 as well. In particular, they found that "dry events in the late 13th, 16th, and 18th Centuries surpass the magnitude and duration of droughts seen in the Uinta Basin after 1900," once again contradicting climate-alarmist "wisdom."

At the other end of the moisture spectrum, Gray *et al.* report that the 20th century was host to two of the strongest wet intervals (1938-1952 and 1965-1987), although these two periods were only the seventh and second most intense wet regimes, respectively, of the entire record. Hence, it would appear that in conjunction with 20th-century global warming, precipitation extremes (both high and low) within northeastern Utah's Uinta Basin have become more *attenuated* as opposed to more *amplified*, in yet another refutation of the climate-alarmist contention that both droughts and floods will become more severe and last longer in a significantly warmer world.

Working in the central and southern Rocky Mountains, Gray *et al.* (2003) examined fifteen tree ring-width chronologies that had been used in previous reconstructions of drought for evidence of low-frequency variations in five regional composite precipitation histories. In doing so, they found that "strong multidecadal phasing of moisture variation was present in all regions during the late 16th-century megadrought," and that "oscillatory modes in the 30-70 year domain persisted until the mid-19th century in two regions, and wet-dry cycles were apparently synchronous at some sites until the 1950s drought." They thus speculate that "severe drought conditions across consecutive seasons and years in the central and southern Rockies may ensue from coupling of the cold phase Pacific Decadal Oscillation with the warm phase Atlantic Multidecadal Oscillation," which is something they envision as having happened in both the severe 1950s drought and the late 16th-century megadrought. Hence, there is reason to believe that episodes of extreme dryness in this part of the country may be driven in part by naturally-recurring climate "regime shifts" in the Pacific and Atlantic Oceans.

Hidalgo *et al.* (2000) used a new form of principal components analysis to reconstruct a history of streamflow in the Upper Colorado River Basin based on information obtained from tree-ring data, after which they compared their results to those of Stockton and Jacoby (1976). In doing so, they found the two approaches to yield similar results, except that Hidalgo *et al.*'s approach responded with more intensity to periods of below-average streamflow or regional drought. Hence, it was easier for them to determine there has been "a near-centennial return period of extreme drought events in this region," going all the way back to the early 1500s. Consequently, it is reasonable to assume that if such an extreme drought were to commence today - which it well could - it would not be long before climate alarmists would be claiming it was caused by CO<sub>2</sub>-induced global warming, when in reality it could well be *totally unrelated* to either the air's CO<sub>2</sub> content or its temperature.

Woodhouse *et al.* (2006) also generated updated proxy reconstructions of water-year streamflow for the Upper Colorado River Basin, based on four key gauges (Green River at Green River, Utah; Colorado near Cisco, Utah; San Juan near Bluff, Utah; and Colorado at Lees Ferry, Arizona) and using an expanded tree-ring network and longer calibration records than in previous efforts. The results of this program indicated that the major drought of 2000-2004, "as measured by 5-year running means of water-year total flow at Lees Ferry ... is not without precedence in the tree ring record," and that "average reconstructed annual flow for the period 1844-1848 was lower." They also report that "two additional periods, in the early 1500s and early 1600s, have a 25% or greater chance of being as dry as 1999-2004," and that six other periods "have a 10% or greater chance of being drier." In addition, their work revealed that "longer duration droughts have occurred in the past," and that "the Lees Ferry reconstruction contains one sequence each of six, eight, and eleven consecutive years with flows below the 1906-1995 average."

"Overall," in the words of the three researchers, "these analyses demonstrate that severe, sustained droughts are a defining feature of Upper Colorado River hydroclimate." In fact, they conclude from their work that "droughts more severe than any 20th to 21st century event occurred in the past," meaning the preceding few centuries; and, of course, this finding is just

the *opposite* of what climate alarmists would have one believe, i.e., that global warming promotes longer lasting droughts of greater severity. In stark contrast to this model-based claim, the real-world record of Upper Colorado River Basin droughts suggests that such devastating climatic conditions are more strongly associated with the much colder temperatures that characterized the Little Ice Age.

Moving closer still to the U.S. border with Mexico - in fact, right up to it - Ni *et al.* (2002) developed a 1000-year history of cool-season (November-April) precipitation for each climate division of Arizona and New Mexico from a network of 19 tree-ring chronologies. In reward for their efforts, they determined that "sustained dry periods comparable to the 1950s drought" occurred in "the late 1000s, the mid 1100s, 1570-97, 1664-70, the 1740s, the 1770s, and the late 1800s." They also note that although the 1950s drought was large in both scale and severity, "it only lasted from approximately 1950 to 1956," whereas the 16th-century mega-drought lasted *more than four times longer*.

With respect to the *opposite* of drought, Ni *et al.* report that "several wet periods comparable to the wet conditions seen in the early 1900s and after 1976" occurred in "1108-20, 1195-1204, 1330-45, the 1610s, and the early 1800s," and they add that "the most persistent and extreme wet interval occurred in the 1330s." Consequently, for the particular part of the world covered by Ni *et al.*'s study, there appears to be nothing unusual about the extremes of both wetness and dryness experienced during the 20th century, which observation is again at odds with the contention of the world's alarmists that global warming should produce extremes of both types, especially since they describe the 20th century as having experienced an *unprecedented warming* that NASA's James Hansen claims has brought the world to within less than one degree of the all-time record high temperature of the last *million or more years*.

Also working in New Mexico, Rasmussen *et al.* (2006) derived a record of regional relative moisture from variations in the annual band thickness and mineralogy of two columnar stalagmites collected from Carlsbad Cavern and Hidden Cave in the Guadalupe Mountains near the New Mexico/Texas border. From this work they discovered that both records "suggest periods of dramatic precipitation variability over the last 3000 years, exhibiting large shifts *unlike anything seen in the modern record* [our italics]." These findings again demonstrate that climate alarmists clearly go overboard when they characterize significant droughts and floods of recent times as being unprecedented over the past millennium or more, as well as when they attribute them to CO<sub>2</sub>-induced global warming. Moisture extremes much greater than those of the modern era are neither unusual nor manmade; they are simply a normal part of earth's natural climatic variability.

We come now to two papers that deal with the western United States as a whole. In the first, Cook *et al.* (2004) developed a 1200-year history of drought for the western half of the country and adjacent parts of Canada and Mexico (hereafter the "West"), based on annually-resolved tree-ring records of summer-season Palmer Drought Severity Index that were derived for 103 points on a 2.5° x 2.5° grid, 68 of which grid points (66% of them) possessed data that extended back to AD 800. This reconstruction, in the words of Cook *et al.*, revealed "some remarkable

earlier increases in aridity that *dwarf* [our italics] the comparatively short-duration current drought in the 'West'." Interestingly, they report that "the four driest epochs, centered on AD 936, 1034, 1150 and 1253, all occur during a ~400 year interval of overall elevated aridity from AD 900 to 1300," which they say is "broadly consistent with the Medieval Warm Period."

Commenting on their findings, the five scientists say "the overall coincidence between our megadrought epoch and the Medieval Warm Period suggests that anomalously warm climate conditions during that time may have contributed to the development of more frequent and persistent droughts in the 'West'," as well as the megadrought that was discovered by Rein *et al.* (2004) to have occurred in Peru at about the same time (AD 800-1250); and after citing nine other studies that provide independent evidence of drought during this time period for various sub-regions of the West, they warn that "any trend toward warmer temperatures in the future could lead to a serious long-term increase in aridity over western North America," noting that "future droughts in the 'West' of similar duration to those seen prior to AD 1300 would be disastrous."

We certainly agree with Cook *et al.*'s analysis, noting that such an unfortunate fate could well befall the western United States, *even in the absence of (likely miniscule) CO<sub>2</sub>-induced global warming*; for the millennial-scale oscillation of climate that brought the world the Medieval Warm Period (which was obviously *not* CO<sub>2</sub>-induced) could well be in process of repeating itself during the possibly still-ongoing development of the Modern Warm Period. In addition, if the association between global warmth and drought in the western United States is robust, it suggests that current world temperatures are still *far below* those experienced during large segments of the Medieval Warm Period.

The last of the two papers to cover the western United States as a whole is that of Woodhouse (2004), who reports what is known about *natural* hydroclimatic variability throughout the region via descriptions of several major droughts that occurred there over the past three millennia, all but the last century of which had atmospheric CO<sub>2</sub> concentrations that never varied by more than about 10 ppm from a mean value of 280 ppm.

For comparative purposes, Woodhouse begins by noting that "the most extensive U.S. droughts in the 20th century were the 1930s Dust Bowl and the 1950s droughts." The first of these droughts lasted "most of the decade of the 1930s" and "occurred in several waves," while the latter "also occurred in several waves over the years 1951-1956." Far more severe than either of these two droughts was what has come to be known as the *16th-Century Megadrought*, which lasted from 1580 to 1600 and included northwestern Mexico in addition to the southwestern United States and the western Great Plains. Then there was what is simply called *The Great Drought*, which spanned the last quarter of the 13th century and was actually the last in a series of *three* 13th-century droughts, the first of which may have been even more severe than the last. In addition, Woodhouse notes there was a period of remarkably sustained drought in the second half of the 12th century.

It is evident from these observations, according to Woodhouse, that "the 20th century climate record contains only a subset of the range of natural climate variability in centuries-long and longer paleoclimatic records." It is also obvious that this subset, as it pertains to water shortage, does not even *begin* to approach the level of drought severity and duration experienced in prior centuries and millennia. This being the case, it is also clear it would take a drought *much* more extreme than the most extreme droughts of the 20th century to propel the western United States and adjacent portions of Canada and Mexico into a truly unprecedented state of dryness.

We can also conclude from these observations that alarmist claims that we are *already* feeling the climatic effects of anthropogenic CO<sub>2</sub> emissions - as manifest in various types of extreme weather phenomena - are *totally without merit*, especially with respect to droughts in the western United States. And that is about all that needs to be said in characterizing the core findings of the papers reviewed above.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/d/droughtusawest.php>.

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#### 5.1.4.3.4. ENTIRE UNITED STATES

What do studies that have focused on the entirety of the conterminous United States reveal about the moisture status of the 20th century and its relationship to global warming? We here address this question via a brief discussion of the findings of several pertinent papers.

Andreadis and Lettenmaier (2006) examined 20th-century trends in soil moisture, runoff and drought over the conterminous United States with a hydro-climatological model forced by real-world measurements of precipitation, air temperature and wind speed over the period 1915-2003. This work revealed, in their words, that "droughts have, for the most part, become shorter, less frequent, less severe, and cover a smaller portion of the country over the last century," in an absolutely *stunning rebuke* of climate-alarmist claims concerning global warming and its effects on drought. What makes this rebuke even more impressive is that climate

alarmists have long claimed earth's temperature in the latter part of the 20th century was *unprecedented over the past millennium*, and that NASA's James Hansen is now claiming the planet's current mean temperature is within less than one degree Centigrade of the warmest temperature of the past *million* years. Clearly, either the temperature-drought relationship they promote is *totally wrong* or their claims of current unprecedented warmth are *way off base*. Or, as we shall see at the conclusion of this section, perhaps each claim is but *moderately* off the mark.

Using the *self-calibrating Palmer (1965) drought severity index (SCPDSI)*, as described by Wells *et al.* (2004), Van der Schrier *et al.* (2006) constructed maps of summer moisture availability across a large portion of North America (20-50°N, 130-60°W) for the period 1901-2002 with a spatial latitude/longitude resolution of 0.5° x 0.5°. This operation revealed, in their words, that over the area as a whole, "the 1930s and 1950s stand out as times of persistent and exceptionally dry conditions, whereas the 1970s and the 1990s were generally wet." However, they say that "no statistically significant trend was found in the mean summer SCPDSI over the 1901-2002 period, nor in the area percentage with moderate or severe moisture excess or deficit." In fact, they could not find *a single coherent area* within the SCPDSI maps that "showed a statistically significant trend over the 1901-2002 period," once again demonstrating that one of the major calamitous predictions of the world's climate alarmists (that more dramatic droughts accompany global warming) is found to be *totally unsupported* by real-world data over a vast area of North America, including the conterminous United States.

Going back considerably further in time, Fye *et al.* (2003) developed gridded reconstructions of the summer (June-August) *basic* Palmer Drought Severity Index over the continental United States, based on "annual proxies of drought and wetness provided by 426 climatically sensitive tree-ring chronologies." This work revealed that the greatest 20th-century moisture anomalies across the United States were the 13-year pluvial over the West in the early part of the century, and the epic droughts of the 1930s (the Dust Bowl years) and 1950s, which lasted 12 and 11 years, respectively; and in comparing these events to earlier wet and dry periods, they made the following points.

The 13-year pluvial from 1905 to 1917 had three earlier analogs: an extended 16-year pluvial from 1825 to 1840, a prolonged 21-year wet period from 1602 to 1622, and a 10-year pluvial from 1549 to 1558. The 11-year drought from 1946 to 1956, on the other hand, had at least *twelve* earlier analogs in terms of location, intensity and duration; but the Dust Bowl drought was greater than all of them ... *except* for a sixteenth-century "megadrought," which lasted some 18 years and was, in the words of Fye *et al.*, "the most severe sustained drought to impact North America in the past 500 to perhaps 1000 years."

In another long-term study, Stahle *et al.* (2000) developed a long-term history of North American drought from reconstructions of the Palmer Drought Severity Index based on analyses of many lengthy tree-ring records. This history also revealed that the 1930s Dust Bowl drought in the United States was eclipsed in all three of these categories by the 16th-century *megadrought*. This incredible period of dryness, as they describe it, persisted "from the 1540s

to 1580s in Mexico, from the 1550s to 1590s over the [U.S.] Southwest, and from the 1570s to 1600s over Wyoming and Montana." In addition, it "extended across most of the continental United States during the 1560s," and it recurred with greater intensity over the Southeast during the 1580s to 1590s. So horrendous were its myriad impacts, Stahle *et al.* unequivocally state that "the 'megadrought' of the 16th century far exceeded any drought of the 20th century." In fact, they state that a "precipitation reconstruction for western New Mexico suggests that the 16th-century drought was the most extreme prolonged drought in the past 2000 years."

Last of all, we come to the intriguing study of Herweijer *et al.* (2006), who begin the report of their work by noting that "drought is a recurring major natural hazard that has dogged civilizations through time and remains the 'world's costliest natural disaster'." With respect to the 20th century, for example, they report that the "major long-lasting droughts of the 1930s and 1950s covered large areas of the interior and southern states and have long served as paradigms for the social and economic cost of sustained drought in the USA." However, they add that "these events are not unique to the twentieth century," and they go on to describe three periods of widespread and persistent drought in the latter half of the nineteenth century - 1856-1865 (the "Civil War" drought), 1870-1877 and 1890-1896 - based on evidence obtained from proxy, historical and instrumental data.

With respect to the first of these impressive mid- to late-19th-century droughts, Herweijer *et al.* say it "is likely to have had a profound ecological and cultural impact on the interior USA, with the persistence and severity of drought conditions in the Plains surpassing those of the infamous 1930s Dust Bowl drought." In addition, they report that "drought conditions during the Civil War, 1870s and 1890s droughts were not restricted to the summer months, but existed year round, with a large signal in the winter and spring months."

Taking a still longer look back in time, the three researchers cite the work of Cook and Krusic (2004), who constructed a North American Drought Atlas using hundreds of tree-ring records. This atlas reveals what Herweijer *et al.* describe as "a 'Mediaeval Megadrought' that occurred from AD 900 to AD 1300," along with "an abrupt shift to wetter conditions after AD 1300, coinciding with the 'Little Ice Age', a time of globally cooler temperatures" that ultimately gave way to "a return to more drought-prone conditions beginning in the nineteenth century."

The broad picture that emerges from these observations is one where the most severe North American droughts of the past millennium were associated with the globally-warmer temperatures of the Medieval Warm Period plus the initial stage of the globally-warmer Current Warm Period. Superimposed upon this low-frequency behavior, however, Herweijer *et al.* find evidence for a "linkage between a colder eastern equatorial Pacific and persistent North American drought over the last 1000 years," noting further that "Rosby wave propagation from the cooler equatorial Pacific amplifies dry conditions over the USA." In addition, they report that after using "published coral data for the last millennium to reconstruct a NINO 3.4 history," they applied "the modern-day relationship between NINO 3.4 and North American drought ... to recreate two of the severest Mediaeval 'drought epochs' in the western USA."

But how is it that simultaneous *global-scale warmth* and *regional-scale cold* combine to produce the most severe North American droughts? The answer fits nicely with our view of what drives the millennial-scale oscillation of climate that produced the *global* Medieval Warm Period, Little Ice Age and Current Warm Period, i.e., *variable solar activity*. When solar activity is in an *ascending* mode, the globe as a whole *warms*; but at the same time, to quote from Herweijer *et al.*'s concluding sentence, increased irradiance typically "corresponds to a colder eastern equatorial Pacific and, by extension, increased drought occurrence in North America and other mid-latitude continental regions."

An important implication of these observations is that the most severe North American droughts should occur during major multi-centennial global warm periods, as has in fact been observed to be the case; and since the greatest such droughts of the Current Warm Period have not yet approached the severity of those that occurred during the Medieval Warm Period, it seems a good bet that the global temperature of the Current Warm Period is not yet as high as the global temperature that prevailed throughout the Medieval Warm Period.

And this implication, of course, begets one further implication: since the Medieval Warm Period was likely warmer than the Current Warm Period has been to date (see also, in this regard, our previous discussion on the Medieval Warm Period, herein), and since it achieved such warmth when there was approximately 25% *less* CO<sub>2</sub> in the air than there is today, there is no need to believe that the historical and still-ongoing rise in the air's CO<sub>2</sub> content has had much at all to do with the creation of our current warmth.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/d/droughtusa.php>.

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## **5.2. Floods**

In evaluating the model-based claim that anthropogenic-induced global warming will lead to intensified flooding around the globe, it is instructive to see how flood activity has responded to the global warming of the past century or so, much of which is claimed by climate alarmists to be due to anthropogenic greenhouse gas emissions. In this section, we thus review several studies of the subject that have been conducted in Asia, Europe and North America.

Additional information on this topic, including reviews on floods not discussed here, can be found at [http://www.co2science.org/subject/f/subject\\_f.php](http://www.co2science.org/subject/f/subject_f.php) under the heading Floods.

### **5.2.1. Asia**

In a study that covered the entire continent, Cluis and Laberge (2001) analyzed the flow records of 78 rivers distributed throughout the entire Asia-Pacific region to see if there had been any enhancement of earth's hydrologic cycle coupled with an increase in variability that might have led to more floods between the mean beginning and end dates of the flow records:  $1936 \pm 5$  years and  $1988 \pm 1$  year, respectively. Over this period, the two scientists determined that *mean* river discharges were *unchanged* in 67% of the cases investigated; and where there were trends, 69% of them were *downward*. In addition, *maximum* river discharges were *unchanged* in 77% of the cases investigated; and where there were trends, 72% of them were *downward*. Consequently, and contrary to climate-alarmist claims of global warming leading to more frequent and more severe flooding, the two researchers observed no changes in both of these flood characteristics in the majority of the rivers they studied; and where there were changes, more of them were of the type that typically leads to *less* flooding and *less severe* floods.

Two years later, Kale *et al.* (2003) conducted geomorphic studies of slackwater deposits in the bedrock gorges of the Tapi and Narmada Rivers of central India, which allowed them to assemble long chronologies of large floods of these rivers. In doing so, they found that "since 1727 at least 33 large floods have occurred on the Tapi River and the largest on the river occurred in 1837." With respect to large floods on the Narmada River, they reported at least 9-10 floods between the beginning of the Christian era and AD 400; while between AD 400 and 1000 they documented 6-7 floods, between 1000 and 1400 about 8-9 floods, and after 1950

three more such floods. In addition, on the basis of texture, elevation and thickness of the flood units, they concluded that "the periods AD 400-1000 and post-1950 represent periods of extreme floods."

What do these findings imply about the effects of global warming on central India flood events? The post-1950 period would likely be claimed by climate alarmists to have been the warmest of the past millennium; and it has indeed experienced some extreme floods. However, the flood characteristics of the 400-1000 period are described in equivalent terms; and this was a rather cold climatic interval known as the Dark Ages Cold Period [see, for example, McDermott *et al.* (2001) and Andersson *et al.* (2003)]. In addition, the most extreme flood in the much shorter record of the Tapi River occurred in 1837, near the beginning of one of the colder periods of the Little Ice Age. Hence, there would appear to be little correlation between the flood characteristics of the Tapi and Narmada Rivers of central India and the thermal state of the global climate.

Focusing on the much smaller area of southwestern Turkey, Touchan *et al.* (2003) developed two reconstructions of spring (May-June) precipitation from tree-ring width measurements, one of them (1776-1998) based on nine chronologies of *Cedrus libani*, *Juniperus excelsa*, *Pinus brutia* and *Pinus nigra*, and the other one (1339-1998) based on three chronologies of *Juniperus excelsa*. These reconstructions, in their words, "show clear evidence of multi-year to decadal variations in spring precipitation," with both wet and dry periods of 1-2 years duration being well distributed throughout the record. However, in the case of more *extreme* hydrologic events, they found that *all* of the wettest 5-year periods *preceded* the Industrial Revolution, manifesting themselves at times when the air's carbon dioxide content was largely unaffected by anthropogenic CO<sub>2</sub> emissions.

Two years later, Jiang *et al.* (2005) analyzed pertinent historical documents to produce a 1000-year time series of flood and drought occurrence in the Yangtze Delta of Eastern China (30 to 33°N, 119 to 122°E), which with a nearly-level plain that averages only two to seven meters above sea level across 75% of its area is vulnerable to flooding and maritime tidal hazards. This work demonstrated that alternating wet and dry episodes occurred throughout the 1000-year period, with the most rapid and strongest of these fluctuations occurring during the *Little Ice Age* (1500-1850).

The following year, Davi *et al.* (2006) developed a reconstruction of streamflow that extended from 1637 to 1997, based on absolutely dated tree-ring-width chronologies from five sampling sites in west-central Mongolia, all of which sites were in or near the Selenge River basin, the largest river in Mongolia. Of the ten wettest five-year periods, only two occurred during the 20th century (1990-1994 and 1917-1921, the second and eighth wettest of the ten extreme periods, respectively), once again indicative of a propensity for *less* flooding during the *warmest* portion of the 360-year period.

The year 2007 produced a second study of the Yangtze Delta of Eastern China, when Zhang *et al.* (2007) developed flood and drought histories of the past thousand years "from local

chronicles, old and very comprehensive encyclopaedia, historic agricultural registers, and official weather reports," after which "continuous wavelet transform was applied to detect the periodicity and variability of the flood/drought series" and, finally, the results of the entire set of operations were compared with 1000-year temperature histories of northeastern Tibet and southern Tibet. This work revealed, in the words of the researchers, that "colder mean temperature in the Tibetan Plateau usually resulted in higher probability of flood events in the Yangtze Delta region," and they say that "during AD 1400-1700 [the coldest portion of their record, corresponding to much of the Little Ice Age], the proxy indicators showing the annual temperature experienced larger variability (larger standard deviation), and this time interval *exactly* [our italics] corresponds to the time when the higher and significant wavelet variance occurred." In contrast, they report that "during AD 1000-1400 [the warmest portion of their record, corresponding to much of the Medieval Warm Period], relatively stable changes of climatic changes reconstructed from proxy indicators in Tibet correspond to lower wavelet variance of flood/drought series in the Yangtze Delta region."

Contemporaneously, Huang *et al.* (2007) constructed a complete catalog of Holocene *overbank flooding events* at a watershed scale in the headwater region of the Sushui River within the Yuncheng Basin in the southeast part of the middle reaches of China's Yellow River, based on pedo-sedimentary records of the region's semiarid piedmont alluvial plains, including the color, texture and structure of the sediment profiles, along with determinations of particle-size distributions, magnetic susceptibilities and elemental concentrations. This work revealed there were six major episodes of overbank flooding. The first occurred at the onset of the Holocene, the second immediately *before* the mid-Holocene Climatic Optimum, and the third in the *late stage* of the mid-Holocene Climatic Optimum, while the last three episodes coincided with "the cold-dry stages during the late Holocene," according to the six scientists. Speaking of the last of the overbank flooding episodes, they note that it "corresponds with the well documented 'Little Ice Age,' when "climate departed from its long-term average conditions and was unstable, irregular, and disastrous," which is pretty much like the Little Ice Age has been described in many other parts of the world as well.

In light of the findings of these several Asian studies, it is clear they provide *no support whatever* for the claim that global warming leads to more frequent and severe flooding. If anything, they tend to suggest just the *opposite*.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/f/floodsasia.php>.

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### 5.2.2. Europe

Knowledge of the past is an important ingredient of any recipe for accurately predicting the future. If one desires to know how flood characteristics might change if the earth continues its post-Little Ice Age warming, for example, it would be advisable to determine how these flood properties changed during prior periods of warming and/or cooling. Hence, we here review a few studies of this nature based on data collected in Europe.

Nesje *et al.* (2001) analyzed a sediment core from a lake in southern Norway in an attempt to determine the frequency and magnitude of prior floods in that region. The last thousand years of the record revealed "a period of little flood activity around the Medieval period (AD 1000-1400)," which was followed by a period of extensive flood activity that was associated with the "post-Medieval climate deterioration characterized by lower air temperature, thicker and more long-lasting snow cover, and more frequent storms associated with the 'Little Ice Age'." Hence, this particular study suggests that the post-Little Ice Age warming the earth has experienced for the last century or two - and which could well continue for some time to come - should be leading this portion of the planet into a period of less extensive flooding as opposed to the



more extensive flooding that is typically predicted by climate alarmists to occur most everywhere.

Pirazzoli (2000) analyzed tide-gauge and meteorological data over the period 1951-1997 for the northern portion of the Atlantic coast of France, discovering that the number of atmospheric depressions and strong surge winds in this region "are becoming less frequent." The data also revealed that "ongoing trends of climate variability show a decrease in the frequency and hence the gravity of coastal flooding," which is exactly what would be expected in view of the findings of Nesje *et al.*

Reynard *et al.* (2001) used a continuous flow simulation model to assess the impacts of potential climate and land use changes on flood regimes of the UK's Thames and Severn Rivers; and, as might have been expected of a *model* study, it predicted modest *increases* in the magnitudes of 50-year floods on these rivers when the climate was forced to change as predicted for various global warming scenarios. However, when the modelers allowed forest cover to rise concomitantly, they found that this land use change "acts in the opposite direction to the climate changes and under some scenarios is large enough to fully compensate for the shifts due to climate."

To better determine what might actually happen in the real world, therefore, it is important to consider how the forested areas of the rivers' catchments might change in the future. Two things come into play here. First, if forests are deemed to be important carbon sinks for which countries may get sequestration credits (as envisioned in the Kyoto Protocol), and if nations begin to employ them as such, the UK government may well promote the development of new forests on much of the land in question. Second, as the air's CO<sub>2</sub> content continues to rise, there will be a great *natural* impetus for forests to expand their ranges and grow in areas where grasses now dominate the landscape. Consequently, with man and nature both singing the same tune, so to speak, it is only logical to presume that forests will indeed expand their presence on the river catchments in question and neutralize any *predicted* increases in flood activity in a future high-CO<sub>2</sub> world.

Warming itself may also help in this regard, as per the findings of Starkel (2002), who reviewed what is known about the relationship between extreme weather events and the thermal climate of Europe during the Holocene. This review clearly demonstrated that more extreme fluvial activity was typically associated with cooler time intervals. In recovering from one such period (the Younger Dryas), for example, temperatures in Germany and Switzerland rose by 3-5°C over several decades; and "this fast shift," in Starkel's words, "caused a rapid expansion of forest communities, [a] rise in the upper treeline and higher density of vegetation cover," which led to a "drastic" reduction in sediment delivery from slopes to river channels.

As an example of just how far out of touch with reality the world's climate alarmists are on this topic, we refer to John Hooper's 14 August 2002 article in *The Guardian*, where he notes that in the midst of 2002's massive flooding in Europe, Gallus Cadonau (the managing director of the Swiss Greina Foundation) called for a punitive tariff on U.S. imports to force cooperation on

greenhouse gas emissions, claiming that the flooding "definitely has to do with global warming" and stating that "we must change something now."

Cadonau was joined in this sentiment by Germany's environment minister, Jurgen Trittin, who implied much the same thing when he said "if we don't want this development to get worse, then we must continue with the consistent reduction of environmentally harmful greenhouse gasses." A thorough analysis of historical flood accounts and more recent river-flow data, however, suggests something very different, as noted by Mudelsee *et al.* (2003), who analyzed historical documents from the 11th century to 1850, plus subsequent water stage and daily runoff records from then until 2002, for two of the largest rivers in central Europe: the Elbe and Oder Rivers.

The team of German scientists reported that "for the past 80 to 150 years" -- which climate alarmists typically describe as a period of unprecedented global warming -- "we find a decrease in winter flood occurrence in both rivers, while summer floods show no trend, consistent with trends in extreme precipitation occurrence." These findings clearly indicate that the strident claims of the world's Cadonaus and Trittins don't stand up to scrutiny when compared with reality. As the world has recovered from the global chill of the Little Ice Age, flooding of the Elbe and Oder rivers has *not* materially changed in summer and has actually *decreased* in winter. Blaming anthropogenic CO<sub>2</sub> emissions for the European flooding of 2002 must thus have been a *political ploy*, for it was surely not a reasoned deduction based on scientific evidence.

Another example of similar behavior from this time period occurred on 8 and 9 September 2002, when extreme flooding of the Gardon River in southern France -- which occurred as a result of half a year's rainfall being received in approximately twenty hours -- claimed the lives of a number of people and caused much damage to towns and villages situated adjacent to its channel. The event elicited much coverage in the press; and, in the words of Sheffer *et al.* (2003), "this flood is now considered by the media and professionals to be 'the largest flood on record'," which record extends all the way back to 1890.

Coincidentally -- and fortunately! -- Sheffer *et al.* were in the midst of a study of prior floods of the Gardon River when the recent "big one" hit. Hence, they had data spanning a much longer time period against which to compare its magnitude. Based on their findings, they report that "the extraordinary flood of September 2002 was not the largest by any means," noting that "similar, and even larger floods have occurred several times in the recent past," with three of the five greatest floods they had identified to that point in time occurring over the period AD 1400-1800 during the Little Ice Age. Commenting on these facts, Sheffer *et al.* stated that "using a longer time scale than human collective memory, paleoflood studies can put in perspective the occurrences of the extreme floods that hit Europe and other parts of the world during the summer of 2002." And that perspective clearly shows that even *greater* floods occurred *repeatedly* during the Little Ice Age, which was *the coldest period of the current interglacial*.

One final study to address this subject as it applies to Europe was that of Lindstrom and Bergstrom (2004), who analyzed runoff and flood data from more than 60 discharge stations scattered throughout Sweden, some of which provide information stretching as far back in time as the early to mid 1800s, when Sweden and the world were still experiencing the cold of the Little Ice Age. This analysis led them to discover that the last 20 years of the past century were indeed unusually wet, with a runoff anomaly of +8% compared with the century average. But they also found that "the runoff in the 1920s was comparable to that of the two latest decades," and that "the few observation series available from the 1800s show that the runoff was even higher than recently." What is more, they note that "flood peaks in old data are probably underestimated," which "makes it difficult to conclude that there has really been a significant increase in average flood levels," as is often claimed by climate alarmists and reported in the media. In addition, they say that "no increased frequency of floods with a return period of 10 years or more, could be determined."

With respect to the generality of their findings, Lindstrom and Bergstrom say that conditions in Sweden "are consistent with results reported from nearby countries: e.g. Forland *et al.* (2000), Bering Ovesen *et al.* (2000), Klavins *et al.* (2002) and Hyvarinen (2003)," and that, "in general, it has been difficult to show any convincing evidence of an increasing magnitude of floods (e.g. Roald, 1999) in the near region, as is the case in other parts of the world (e.g. Robson *et al.*, 1998; Lins and Slack, 1999; Douglas *et al.*, 2000; McCabe and Wolock, 2002; Zhang *et al.*, 2001)."

In light of this body of evidence, it is clear that for most of Europe, as well as many other parts of the world, there are simply no compelling real-world data to support the climate-alarmist claim that global warming leads to more frequent and severe flooding. In fact, the *lack* of such evidence over the past century -- which is typically described by climate alarmists as having experienced an increase in global temperature that is *unprecedented* over the past one to two *millennia* -- should surely qualify as proof of the *falsity* of their contentions.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/f/floodseuro.php>.

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### 5.2.3. North America

Lins and Slack (1999) analyzed secular streamflow trends in 395 different parts of the United States that were derived from more than 1500 individual streamgauges, some of which had continuous data stretching all the way back to 1914. In the mean, they found that "the conterminous U.S. is getting wetter, but less extreme." That is to say, as the near-surface air temperature of the planet gradually rose throughout the course of the 20th century, the United States became wetter in the mean but less variable at the extremes, which is where floods and droughts occur, leading to what could well be called *the best of both worlds*, i.e., more water with less floods.

In a similar but more regionally-focused study, Molnar and Ramirez (2001) conducted a detailed analysis of precipitation and streamflow trends for the period 1948-1997 in the semiarid Rio Puerco Basin of New Mexico. At the annual timescale, they reported finding "a statistically significant increasing trend in precipitation," which was driven primarily by an increase in the number of rainy days in the moderate rainfall intensity range, with essentially no change at the high-intensity end of the spectrum. In the case of streamflow, however, there was *no* trend at the annual timescale; but monthly totals increased in low-flow months and decreased in high-flow months, once again reducing the likelihood of both floods and droughts, courtesy of 20th-century warming.

Think of the implications of these findings. Increased precipitation in a semiarid region is a real plus. Having most of the increase in the moderate rainfall intensity range also sounds like a plus. Increasing streamflow in normally low-flow months sounds good too, as does decreasing streamflow in high-flow months. In fact, *all* of the observed changes in precipitation and streamflow in this study would appear to be highly desirable, leading to more water availability but a lowered probability of both floods and droughts, which we could now well call *the best of all worlds*.

Knox (2001) identified an analogous phenomenon in the more mesic Upper Mississippi River Valley, but with a slight twist. Since the 1940s and early 50s, the magnitudes of the largest daily flows in this much wetter region have been decreasing at the same time that the magnitude of the average daily baseflow has been increasing, once again manifesting simultaneous trends towards both lessened flood and drought conditions.

Much the same story is told by the research of Garbrecht and Rossel (2002), who studied the nature of precipitation throughout the U.S. Great Plains over the period 1895-1999. For the central and southern Great Plains, the last two decades of this period were found to be the longest and wettest of the entire 105 years of record, due primarily to a reduction in the number of dry years and an increase in the number of wet years. Once again, however, the number of *very* wet years - which would be expected to produce flooding - "did not increase as much and even showed a decrease for many regions."

The northern and northwestern Great Plains also experienced a precipitation increase near the end of Garbrecht and Rossel's 105-year record; but it was primarily confined to the final decade of the 20th century. And again, as they report, "fewer dry years over the last 10 years, as opposed to an increase in very wet years, were the leading cause of the observed wet conditions."

In spite of the general tendencies described in these several papers, there still were some significant floods during the last decade of the past century, such as the 1997 flooding of the Red River of the North, which devastated Grand Forks, North Dakota, as well as parts of Canada. However, as Haque (2000) reports, although this particular flood was indeed the largest experienced by the Red River over the past century, it was not the largest to occur in historic times. In 1852, for example, there was a slightly larger Red River flood; and in 1826 there was a *much* larger flood that was nearly 40% greater than the flood of 1997. And the temperature of the globe, we hasten to add, was *much colder* at the times of these earlier catastrophic floods than it was in 1997, indicating that one cannot attribute the strength of the 1997 flood to the degree of warmth experienced that year or throughout the preceding decade.

Analogously, Olsen *et al.* (1999) report that some upward trends in flood-flows have been found in certain places along the Mississippi and Missouri Rivers, which is not at all surprising, as there will always be exceptions to the general rule. At the same time, however, they note that many of the observed upward trends were highly dependent upon the length of the data record and when the trends began and ended. Hence, they say of these trends that they "were not necessarily there in the past and they may not be there tomorrow."

Expanding the scope of our vision somewhat, we move next to a consideration of studies that have concerned themselves with much longer intervals of time, beginning with that of Fye *et al.* (2003), who developed multi-century reconstructions of summer (June-August) Palmer Drought Severity Index over the continental United States from annual proxies of moisture status provided by 426 climatically-sensitive tree-ring chronologies. This exercise indicated that the greatest 20th-century wetness anomaly across the United States was the 13-year pluvial that occurred in the early part of the century, when it was considerably colder than it is now. In addition, Fye *et al.*'s analysis revealed the existence of a 16-year pluvial from 1825 to 1840 and a prolonged 21-year wet period from 1602 to 1622, both of which anomalies occurred during the Little Ice Age, when, of course, it was colder still.

St. George and Nielsen (2002) likewise used "a ringwidth chronology developed from living, historical and subfossil bur oak (*Quercus macrocarpa* (Michx.)) in the Red River basin to reconstruct annual precipitation in southern Manitoba since A.D. 1409." Their analysis indicated, in their words, that "prior to the 20th century, southern Manitoba's climate was more extreme and variable, with prolonged intervals that were wetter and drier than any time following permanent Euro-Canadian settlement."

Also working with tree-ring chronologies, Ni *et al.* (2002) developed a 1000-year history of cool-season (November-April) precipitation for each climate division in Arizona and New Mexico,

USA. In doing so, they found that several wet periods comparable to the wet conditions seen in the early 1900s and post-1976 occurred in 1108-20, 1195-1204, 1330-45 (which they denominate "the most persistent and extreme wet interval"), the 1610s, and the early 1800s, all of which wet periods are embedded in the long cold expanse of the Little Ice Age, which is clearly revealed in the work of Esper *et al.* (2002).

Doubling the temporal extent of Ni *et al.*'s investigation, Schimmelmann *et al.* (2003) analyzed gray clay-rich flood deposits in the predominantly olive varved sediments of the Santa Barbara Basin off the coast of California, USA, which they accurately dated by varve-counting. Their analysis indicated that six prominent flood events occurred at approximately AD 212, 440, 603, 1029, 1418 and 1605, "suggesting," in their words, "a quasi-periodicity of ~200 years," with "skipped" flooding just after AD 800, 1200 and 1800. They further note that "the floods of ~AD 1029 and 1605 seem to have been associated with brief cold spells," that "the flood of ~AD 440 dates to the onset of the most unstable marine climatic interval of the Holocene (Kennett and Kennett, 2000)," and that "the flood of ~AD 1418 occurred at a time when the global atmospheric circulation pattern underwent fundamental reorganization at the beginning of the 'Little Ice Age' (Kreutz *et al.*, 1997; Meeker and Mayewski, 2002)." As a result, they hypothesize that "solar-modulated climatic background conditions are opening a ~40-year window of opportunity for flooding every ~200 years," and that "during each window, the danger of flooding is exacerbated by additional climatic and environmental cofactors." They also note that "extrapolation of the ~200-year spacing of floods into the future raises the uncomfortable possibility for historically unprecedented flooding in southern California during the first half of this century." Consequently, if such flooding does occur in the near future, there will be no need to suppose it came as a consequence of what climate alarmists call the unprecedented warming of the past century, although they will surely claim it did.

Once again doubling the length of time investigated, Campbell (2002) analyzed the grain sizes of sediment cores obtained from Pine Lake, Alberta, Canada, to provide a non-vegetation-based high-resolution record of streamflow variability for this part of North America over the past 4000 years. This work revealed that the highest rates of stream discharge during this period occurred during the Little Ice Age, approximately 300-350 years ago, at which time grain sizes were about 2.5 standard deviations above the 4000-year mean. In contrast, the lowest rates of streamflow were observed around AD 1100, during the Medieval Warm Period, when median grain sizes were nearly 2.0 standard deviations *below* the 4000-year mean.

Further extending the temporal scope of our review, Brown *et al.* (1999) analyzed various properties of cored sequences of hemipelagic muds deposited in the northern Gulf of Mexico for evidence of variations in Mississippi River outflow over the past 5300 years. This group of researchers found evidence of seven large *megafloods*, which they describe as "almost certainly larger than historical floods in the Mississippi watershed." In fact, they say these fluvial events were likely "episodes of multidecadal duration," five of which occurred during cold periods similar to the Little Ice Age.

Last of all, in a study that covered essentially the entire Holocene, Noren *et al.* (2002) employed several techniques to identify and date terrigenous in-wash layers found in sediment cores extracted from thirteen small lakes distributed across a 20,000-km<sup>2</sup> region in Vermont and eastern New York that depict the frequency of storm-related floods. Their results indicated, in their words, that "the frequency of storm-related floods in the northeastern United States has varied in regular cycles during the past 13,000 years (13 kyr), with a characteristic period of about 3 kyr." Specifically, they found there were four major peaks in the data during this period, with the most recent upswing in storm-related floods beginning "at about 600 yr BP [Before Present], coincident with the beginning of the Little Ice Age." In addition, they note that several "independent records of storminess and flooding from around the North Atlantic show maxima that correspond to those that characterize our lake records [Brown *et al.*, 1999; Knox, 1999; Lamb, 1979; Liu and Fearn, 2000; Zong and Tooley, 1999]."

Taken together, the research described in this part of the world suggests that, if anything, North American flooding tends to become both *less* frequent and *less* severe when the planet warms, although there have been some exceptions to this general rule. Hence, although there could also be exceptions to this rule in the case of future warming, *on average*, we would expect that any further warming of the globe would tend to further reduce both the frequency and severity of flooding in North America, which, of course, is just the *opposite* of what the world's climate alarmists continue to claim would occur.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/f/floodsnortham.php>.

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### **5.3. Tropical Cyclones**

Climate alarmists contend that global warming promotes increases in both the frequency and intensity of hurricanes. However, there is considerable evidence from numerous peer-reviewed studies which suggest otherwise. In the following section we examine such claims as they pertain to hurricane activity in the Atlantic, Pacific and Indian Ocean basins, as well as for the globe as a whole, beginning first with a discussion on the intensity of Atlantic Basin hurricanes.

#### **5.3.1. Atlantic Ocean**

##### **5.3.1.1 Intensity**

Setting the stage for our discussion, Free *et al.* (2004) write that “increases in hurricane intensity are expected to result from increases in sea surface temperature and decreases in tropopause-level temperature accompanying greenhouse warming (Emanuel, 1987; Henderson-Sellers *et al.*, 1998; Knutson *et al.*, 1998),” but that “because the predicted increase in intensity for doubled CO<sub>2</sub> is only 5%-20%, changes over the past 50 years would likely be less than 2% -- too small to be detected easily.” In addition, they say that “studies of observed frequencies and maximum intensities of tropical cyclones show no consistent upward trend (Landsea *et al.*, 1996; Henderson-Sellers *et al.*, 1998; Solow and Moore, 2002).” In fact, many studies have actually found yearly hurricane numbers to *decline* as temperatures rise (see other reviews this section).

In an application of the old maxim, therefore, that “if at first you don't succeed, try, try again,” Free *et al.* do just that, looking, however, not for increases in *actual* hurricane intensity, but for increases in *potential* hurricane intensity, because, as they describe it, “changes in potential intensity (PI) can be estimated from thermodynamic principles as shown in Emanuel (1986, 1995) given a record of SSTs [sea surface temperatures] and profiles of atmospheric temperature and humidity.” This they thus do, using radiosonde and SST data from 14 island radiosonde stations in the tropical Atlantic and Pacific Oceans, after which they compare their results with those of Bister and Emanuel (2002) at grid points near the selected stations. And when all is said and done, they report that their results “show no significant trend in potential intensity from 1980 to 1995 and no consistent trend from 1975 to 1995.” What is more, they report that between 1975 and 1980, “while SSTs rose, PI decreased, illustrating the hazards of predicting changes in hurricane intensity from projected SST changes alone.”

In the following year, some important new studies once again promoted the climate-alarmist claim that warming does indeed enhance tropical cyclone intensity (Emanuel, 2005; Webster *et al.*, 2005); but a new review of the subject once again cast doubt on this contention. In this publication, Pielke *et al.* (2005) began their discussion by noting that “globally there has been no increase in tropical cyclone *frequency* [our italics] over at least the past several decades,” citing the studies of Lander and Guard (1998), Elsner and Kocher (2000) and Webster *et al.* (2005) in support of this statement. Furthermore, they noted that research on possible future changes in hurricane frequency due to global warming has produced studies that “give such contradictory results as to suggest that the state of understanding of tropical cyclogenesis provides too poor a foundation to base any projections about the future.”

With respect to hurricane *intensity*, on the other hand, Pielke *et al.* noted that Emanuel (2005) claimed to have found “a very substantial upward trend in power dissipation (i.e., the sum over the life-time of the storm of the maximum wind speed cubed) in the North Atlantic and western North Pacific.” However, they report that “other studies that have addressed tropical cyclone intensity variations (Landsea *et al.*, 1999; Chan and Liu, 2004) show no significant secular trends during the decades of reliable records.” In addition, they indicate that although early theoretical work by Emanuel (1987) “suggested an increase of about 10% in wind speed for a 2°C increase in tropical sea surface temperature,” more recent work by Knutson and Tuleya (2004) points to only a 5% increase in hurricane windspeeds by 2080, and that Michaels *et al.* (2005) conclude that even this projection is likely twice as great as it should be.

Perhaps of greatest significance of all to the issue of future hurricanes and the destruction they may cause is the nature and degree of human occupation of exposed coastal areas. By 2050, for example, Pielke *et al.* report that “for every additional dollar in damage that the Intergovernmental Panel on Climate Change expects to result from the effects of global warming on tropical cyclones, we should expect between \$22 and \$60 of increase in damage due to population growth and wealth,” citing the findings of Pielke *et al.* (2000) in this regard. Based on this evidence, they thus state, without equivocation, that “the primary factors that govern the magnitude and patterns of future damages and casualties are how society develops and prepares for storms rather than any presently conceivable future changes in the frequency and intensity of the storms.”

In concluding their review, Pielke *et al.* note that many climate alarmists continue to claim a significant hurricane-global warming connection for the purpose of advocating massive anthropogenic CO<sub>2</sub> emissions reductions that “simply will not be effective with respect to addressing future hurricane impacts,” additionally noting that “there are much, much better ways to deal with the threat of hurricanes than with energy policies (e.g., Pielke and Pielke, 1997).”

In a subsequent analysis of Emanuel’s (2005) and Webster *et al.*’s (2005) claims that “rising sea surface temperatures (SSTs) in the North Atlantic hurricane formation region are linked to recent increases in hurricane intensity, and that the trend of rising SSTs during the past 3 to 4 decades bears a strong resemblance to that projected to occur from increasing greenhouse gas

concentrations," Michaels *et al.* (2006) used weekly-averaged 1° latitude by 1° longitude SST data together with hurricane track data of the National Hurricane Center that provide hurricane-center locations (latitude and longitude in tenths of a degree) and maximum 1-minute surface wind speeds (both at six-hour intervals) for all tropical storms and hurricanes in the Atlantic basin that occurred between 1982 (when the SST data set begins) through 2005. Plotting maximum cyclone wind speed against the maximum SST that occurred prior to (or concurrent with) the maximum wind speed of each of the 270 Atlantic tropical cyclones of their study period, they found that for each 1°C increase in SST between 21.5°C and 28.25°C, the maximum wind speed attained by Atlantic basin cyclones rises, in the mean, by 2.8 m/s, and that thereafter, as SSTs rise still further, the first category-3-or-greater storms begin to appear. *However*, they report "there is no significant relationship between SST and maximum winds at SST exceeding 28.25°C."

From these observations, Michaels *et al.* conclude that "while crossing the 28.25°C threshold is a virtual necessity for attaining category 3 or higher winds, SST greater than 28.25°C does not act to further increase the intensity of tropical cyclones." Hence, it would appear that the comparison of SSTs *actually encountered by individual storms* performed by Michaels *et al.* -- as opposed to the comparisons of Emanuel (2005) and Webster *et al.* (2005), which utilized basin-wide averaged monthly or seasonal SSTs -- refutes the idea that anthropogenic activity has detectably influenced the severity of Atlantic basin hurricanes over the past quarter-century.

Simultaneously, Balling and Cerverny (2006) examined temporal patterns in the frequency of intense tropical cyclones (TCs), the rates of rapid intensification of TCs, and the average rate of intensification of hurricanes in the North Atlantic Basin, including the tropical and subtropical North Atlantic, Caribbean Sea and Gulf of Mexico, where they say there was "a highly statistically significant warming of 0.12°C decade<sup>-1</sup> over the period 1970-2003 ... based on linear regression analysis and confirmed by a variety of other popular trend identification techniques." In doing so, they found "no increase in a variety of TC intensification indices," and that "TC intensification and/or hurricane intensification rates ... are not explained by current month or antecedent sea surface temperatures (despite observed surface warming over the study period)." Hence, they concluded that "while some researchers have hypothesized that increases in long-term sea surface temperature may lead to marked increases in TC storm intensity, our findings demonstrate that various indicators of TC intensification show no significant trend over the recent three decades."

Klotzbach and Gray (2006) note that still other papers question the validity of the findings of Emanuel (2005) and Webster *et al.* (2005) "due to potential bias-correction errors in the earlier part of the data record for the Atlantic basin (Landsea, 2005)," and that "while major hurricane activity in the Atlantic has shown a large increase since 1995, *global* [our italics] tropical-cyclone activity, as measured by the accumulated cyclone energy index, has decreased slightly during the past 16 years (Klotzbach, 2006)." And as a result of these and other data and reasoning described in their paper, they "attribute the heightened Atlantic major hurricane activity of the 2004 season as well as the increased Atlantic major hurricane activity of the previous nine years to be a consequence of multidecadal fluctuations in the strength of the Atlantic multidecadal

mode and strength of the Atlantic Ocean thermohaline circulation." In this regard, for example, they say "historical records indicate that positive and negative phases of the Atlantic multidecadal mode and thermohaline circulation last about 25-30 years (typical period ~50-60 years; Gray *et al.*, 1997; Latif *et al.*, 2004)," and that "since we have been in this new active thermohaline circulation period for about 11 years, we can likely expect that most of the next 15-20 hurricane seasons will also be active, particularly with regard to increased major hurricane activity," demonstrating that the science of this subject is far from "settled," in contrast to what the world's climate alarmists typically contend.

Also referencing the debate over the impact of global warming on hurricane intensity, Vecchi and Soden (2007a) explored 21<sup>st</sup>-century projected changes in *vertical wind shear* (VS) over the tropical Atlantic and its ties to the Pacific Walker circulation via a suite of coupled ocean-atmosphere models forced by emissions scenario A1B (atmospheric CO<sub>2</sub> stabilization at 720 ppm by 2100) of the Intergovernmental Panel on Climate Change's 4<sup>th</sup> Assessment Report, where VS is defined as the magnitude of the vector difference between monthly mean winds at 850 and 200 hPa, and where changes are computed between the two 20-year periods 2001-2020 and 2081-2100. The 18-model mean result indicated a prominent increase in VS over the tropical Atlantic and East Pacific (10°N-25°N); and noting that "the relative amplitude of the shear increase in these models is comparable to or larger than model-projected changes in other large-scale parameters related to tropical cyclone activity," the two researchers went on to state that the projected changes "would not suggest a strong anthropogenic increase in tropical Atlantic or Pacific hurricane activity during the 21<sup>st</sup> Century," and that "in addition to impacting cyclogenesis, the increase in SER [shear enhancement region] shear could act to inhibit the intensification of tropical cyclones as they traverse from the MDR [main development region] to the Caribbean and North America." Consequently, and in addition to the growing body of *empirical* evidence that indicates global warming has little to no impact on the intensity of hurricanes (Donnelly and Woodruff, 2007; Nyberg *et al.*, 2007), there is now considerable up-to-date *model*-based evidence for the same conclusion.

In a second closely related paper, Vecchi and Soden (2007b) used both climate models and observational reconstructions "to explore the relationship between changes in sea surface temperature and tropical cyclone 'potential intensity' -- a measure that provides an upper bound on cyclone intensity and can also reflect the likelihood of cyclone development." In doing so, they found, as they describe it, that "changes in local sea surface temperature are inadequate for characterizing *even the sign* [our italics] of changes in potential intensity." Instead, they report that "long-term changes in potential intensity are closely related to the regional structure of warming," such that "regions that warm more than the tropical average are characterized by increased potential intensity, and vice versa." Using this relationship to reconstruct changes in potential intensity over the 20<sup>th</sup> century, based on observational reconstructions of sea surface temperature, they further found that "even though tropical Atlantic sea surface temperatures are currently at a historical high, Atlantic potential intensity probably peaked in the 1930s and 1950s," noting that "recent values are near the historical average." Consequently, the ultimate conclusion of the two scientists was that the response of tropical cyclone activity to natural climate variations "may be larger than the response to the

more uniform patterns of greenhouse-gas-induced warming," which further suggests, in our estimation, that climate-alarmist attempts to blame any recent *imagined* increases -- or any near-future *real* increases -- in either cyclone numbers or intensities on CO<sub>2</sub>-induced global warming would be totally unjustified, based on our present state of knowledge.

Also in the year 2007, and at the same time that Vecchi and Soden were conducting their studies of the subject, Latif *et al.* (2007) were hard at work analyzing the 1851-2005 history of Accumulated Cyclone Energy or ACE Index for the Atlantic basin, which parameter, in their words, "takes into account the number, strength and duration of all tropical storms in a season," after which they "analyzed the results of an atmospheric general circulation model forced by the history of observed global monthly sea surface temperatures for the period 1870-2003."

With respect to the first part of their study, they report that "the ACE Index shows pronounced multidecadal variability, with enhanced tropical storm activity during the 1890s, 1950s and at present, and mostly reduced activity in between, but *no sustained long-term trend* [our italics]," while with respect to the second part of their study, they report that "a clear warming trend is seen in the tropical North Atlantic sea surface temperature," but that this warming trend "*does not seem to influence the tropical storm activity* [our italics again]."

This state of affairs seemed puzzling at first, because a warming of the tropical North Atlantic is known to reduce vertical wind shear there and thus promote the development of tropical storms. However, Latif *et al.*'s modeling work revealed that a warming of the tropical Pacific *enhances* the vertical wind shear over the *Atlantic*, as does a warming of the tropical Indian Ocean. Consequently, they learned, as they describe it, that "the response of the vertical wind shear over the tropical Atlantic to a warming of all three tropical oceans, as observed during the last decades, will depend on the warming of the Indo-Pacific relative to that of the tropical North Atlantic," and "apparently," as they continue, "the warming trends of the three tropical oceans cancel with respect to their effects on the vertical wind shear over the tropical North Atlantic, so that the tropical cyclone activity [has] remained rather stable and mostly within the range of the natural multidecadal variability."

Nevertheless, a striking exception to this general state of affairs occurred in 2005, when the researchers report that "the tropical North Atlantic warmed more rapidly than the Indo-Pacific," which reduced vertical wind shear over the North Atlantic, producing the most intense Atlantic hurricane season of the historical record. In contrast, they say that the summer and fall of 2006 were "characterized by El Niño conditions in the Indo-Pacific, leading to a rather small temperature difference between the tropical North Atlantic and the tropical Indian and Pacific Oceans," and they say that "this explains the weak tropical storm activity [of that year]."

Clearly, the temperature/hurricane connection is nowhere near as "one-dimensional" as Al Gore and others make it out to be. Warming alone does *not* imply that *hurricanes are getting stronger*. Rather, as Latif *et al.* describe it, "the future evolution of Atlantic tropical storm activity will critically depend on the warming of the tropical North Atlantic *relative to that in the*

*Indo-Pacific region* [our italics],” and in this context they note that “changes in the meridional overturning circulation and their effect on tropical Atlantic sea surface temperatures have to be considered,” and that “changes in ENSO statistics in the tropical Pacific may become important.” Consequently, it is anyone’s guess as to what would actually occur in the real world if the earth were to experience additional substantial warming. However, since the global temperature rise of the 20<sup>th</sup>-century -- which climate alarmists contend was *unprecedented* over the past two *millennia* -- did not lead to a sustained long-term increase in hurricane intensity, there is little reason to believe that any further warming would do so.

In one final concurrent study, Scileppi and Donnelly (2007) note that “when a hurricane makes landfall, waves and storm surge can overtop coastal barriers, depositing sandy overwash fans on backbarrier salt marshes and tidal flats,” and that long-term records of hurricane activity are thus formed “as organic-rich sediments accumulate over storm-induced deposits, preserving coarse overwash layers.” Based on this knowledge, they refined and lengthened the hurricane record of the New York City area by first calibrating the sedimentary record of surrounding backbarrier environments to documented hurricanes -- including those of 1893, 1821, 1788 and 1693 -- and then extracting several thousand additional years of hurricane history from this important sedimentary archive.

As a result of these efforts, the two researchers determined that “alternating periods of quiescent conditions and frequent hurricane landfall are recorded in the sedimentary record and likely indicate that climate conditions may have modulated hurricane activity on millennial timescales.” Of special interest in this regard, as they describe it, is the fact that “several major hurricanes occur in the western Long Island record during the latter part of the Little Ice Age (~1550-1850 AD) when sea surface temperatures were generally colder than present,” but that “no major hurricanes have impacted this area since 1893,” when the earth experienced the warming that took it from the Little Ice Age to the Current Warm Period.

Noting that Emanuel (2005) and Webster *et al.* (2005) had produced analyses that suggest that “cooler climate conditions in the past may have resulted in fewer strong hurricanes,” but that their own findings suggest just the *opposite*, Scileppe and Donnelly concluded that “other climate phenomena, such as atmospheric circulation, may have been favorable for intense hurricane development despite lower sea surface temperatures” prior to the development of the Current Warm Period. Perhaps, therefore, we have much-maligned *global warming* to thank for the *complete absence* of major hurricanes in the vicinity of New York City over the past 115 years.

Last of all, Briggs (2008) developed Bayesian statistical models for the number of tropical cyclones, the rate at which these cyclones became hurricanes, and the rate at which the hurricanes became category 4+ storms in the North Atlantic, based on data from 1966 to 2006; and this work led him to conclude that there is “no evidence that the distributional mean of individual storm intensity, measured by storm days, track length, or individual storm power dissipation index, has changed (increased or decreased) through time.”

In light of the many real-world observations (as well as certain modeling work) discussed above, it would appear that even the supposedly unprecedented global warming of the past century or more has *not* led to an increase in the intensity of Atlantic hurricanes, as so many climate alarmists unabashedly claim it has.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/h/hurratlanintensity.php>.

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### 5.3.1.2. Frequency

#### 5.3.1.2.1. THE PAST FEW MILLENNIA

Has the warming of the past century increased the yearly number of intense Atlantic Basin hurricanes? We investigate this question via a brief review of some studies that have explored this question via thousand-year reconstructions of the region's intense hurricane activity.

Liu and Fearn (1993) analyzed sediment cores retrieved from the center of Lake Shelby in Alabama (USA) to determine the history of intense (category 4 and 5) hurricane activity there

over the past 3,500 years. This work revealed that over the period of their study, "major hurricanes of category 4 or 5 intensity directly struck the Alabama coast ... with an average recurrence interval of ~600 years." They also report that the last of these hurricane strikes occurred about 700 years ago. Hence, it would appear that 20<sup>th</sup>-century global warming has not accelerated the occurrence of such severe storm activity.

Seven years later, Liu and Fern (2000) conducted a similar study based on sixteen sediment cores retrieved from Western Lake, Florida (USA), which they used to produce a proxy record of intense hurricane strikes for this region of the Gulf of Mexico that covered the past 7000 years. In this study, twelve major hurricanes of category 4 or 5 intensity were found to have struck the Western Lake region. Nearly all of these events were centered around a 2400-year period between 1000 and 3400 years ago, when 11 of the 12 events were recorded. In contrast, between 0 to 1000 and 3400 to 7000 years ago, only one and zero major hurricane strikes were recorded, respectively. According to the two researchers, a probable explanation for the "remarkable increase in hurricane frequency and intensity" that affected the Florida Panhandle and the Gulf Coast after 1400 BC would have been a continental-scale shift in circulation patterns that caused the jet stream to shift *south* and the Bermuda High *southwest* of their earlier Holocene positions, such as would be expected with global *cooling*, giving strength to their contention that "paleohurricane records from the past century or even the past millennium are not long enough to capture the full range of variability of catastrophic hurricane activities inherent in the Holocene climatic regime."

Consequently, the next time a major Atlantic hurricane makes landfall somewhere on the Gulf Coast of the United States, don't give in to climate-alarmist hype and immediately point the finger of blame at global warming. Such occurrences may well fall within the range of millennial-scale climate variability. And remember, also, that from 3400 to 7000 years ago, the earth was experiencing what is known as the Holocene Maximum, which was *the warmest period of the current interglacial*. And that 3600-year period saw *zero* category 4 or 5 intensity hurricanes in the Western Lake region of Florida.

Last of all, we have the study of Donnelly and Woodruff (2007), who state that "it has been proposed that an increase in sea surface temperatures caused by anthropogenic climate change has led to an increase in the frequency of intense tropical cyclones," citing the studies of Emanuel (2005) and Webster *et al.* (2005), which is also the view Al Gore expressed in his 21 March 2007 testimony to the U.S. Senate's Environment & Public Works Committee. Thus cognizant of the great need to have a much longer record of the frequency of occurrence of intense hurricanes than that used by Emanuel and Webster *et al.* to draw the politically-charged conclusions Mr. Gore and others have since been championing, Donnelly and Woodruff developed "a record of intense [category 4 and greater] hurricane activity in the western North Atlantic Ocean over the past 5,000 years based on sediment cores from a Caribbean lagoon [Laguna Playa Grande on the island of Vieques, Puerto Rico] that contains coarse-grained deposits associated with intense hurricane landfalls."

Based on this work, the two researchers from the Woods Hole Oceanographic Institution

detected three major intervals of intense hurricane strikes: one between 5,400 and 3,600 calendar years before present (yr BP, where “present” is AD 1950), one between 2,500 and 1,000 yr BP, and one after 250 yr BP. They also report that coral-based sea surface temperature (SST) data from Puerto Rico “indicate that mean annual Little Ice Age (250-135 yr BP or AD 1700-1815) SSTs were 2-3°C cooler than they are now,” and they say that “an analysis of Caribbean hurricanes documented in Spanish archives indicates that 1766-1780 was one of the most active intervals in the period between 1500 and 1800 (Garcia-Herrera *et al.*, 2005), when tree-ring-based reconstructions indicate a negative (cooler) phase of the Atlantic Multidecadal Oscillation (Gray *et al.*, 2004).”

In light of these findings, Donnelly and Woodruff concluded that “the information available suggests that tropical Atlantic SSTs were probably not the principal driver of intense hurricane activity over the past several millennia.” Indeed, there is *no compelling reason* to believe that the current level of intense hurricane activity is in any way unprecedented or that it has been caused by global warming, in contrast to what climate alarmists continue to claim. Quite to the contrary, the two researchers write that “studies relying on recent climatology indicate that North Atlantic hurricane activity is greater during [cooler] La Niña years and suppressed during [warmer] El Niño years (Gray, 1984; Bove *et al.*, 1998), due primarily to increased vertical wind shear in strong El Niño years hindering hurricane development.”

In summary, millennial-scale reconstructions of intense hurricane activity within the Atlantic Basin provide no support for the claim that global warming will lead to the creation of more intense Atlantic hurricanes that will batter the east, southeast, and southern coasts of the United States. In fact, they suggest just the *opposite*.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/h/hurratlanmill.php>.

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#### 5.3.1.2.2. THE PAST FEW CENTURIES

Has the warming of the past century, which rescued the world from the extreme cold of the Little Ice Age, led to the yearly formation of more numerous Atlantic Basin tropical storms and hurricanes? We investigate this question via a brief review of several studies that have broached this question with sufficiently-long databases to provide reliable answers.

Elsner *et al.* (2000) provided a statistical and physical basis for understanding regional variations in major hurricane activity along the U.S. coastline on long timescales; and in doing so, they presented data on major hurricane occurrences in 50-year intervals for Bermuda, Jamaica and Puerto Rico. These data revealed that hurricanes occurred at *far* lower frequencies in the last half of the 20<sup>th</sup> century than they did in the preceding *five* 50-year periods, and at *all three* of the locations studied. From 1701 to 1850, for example, when the earth was locked in the icy grip of the Little Ice Age, major hurricane frequency was 2.77 times greater at Bermuda, Jamaica and Puerto Rico than it was from 1951 to 1998; and from 1851 to 1950, when the planet was in transition from Little Ice Age to current conditions, the three locations experienced a mean hurricane frequency that was 2.15 times greater than what they experienced from 1951 to 1998.

Boose *et al.* (2001) used historical records to reconstruct hurricane damage regimes for an area composed of the six New England states plus adjoining New York City and Long Island for the period 1620-1997. In describing their findings, they wrote that “there was no clear century-scale trend in the number of major hurricanes.” At lower damage levels, however, fewer hurricanes were recorded in the 17<sup>th</sup> and 18<sup>th</sup> centuries than in the 19<sup>th</sup> and 20<sup>th</sup> centuries; but the three researchers concluded that “this difference is probably the result of improvements in meteorological observations and records since the early 19<sup>th</sup> century.” Hence, confining ourselves to the better records of the last 200 years, we note that the cooler 19<sup>th</sup> century had five of the highest-damage storms, while the warmer 20<sup>th</sup> century had only one such storm.

Nyberg *et al.* (2007) developed a history of major (category 3-5) Atlantic hurricanes over the past 270 years based on proxy records of *vertical wind shear* and *sea surface temperature* that they derived from corals and a marine sediment core. These parameters are the primary controlling forces that set the stage for the formation of major hurricanes in the main development region westward of Africa across the tropical Atlantic and Caribbean Sea between latitudes 10 and 20°N, where 85% of all major hurricanes and 60% of all non-major hurricanes and tropical storms of the Atlantic are formed. This effort resulted in their discovering that the average frequency of major Atlantic hurricanes “decreased gradually from the 1760s until the early 1990s, reaching anomalously low values during the 1970s and 1980s.” More specifically, they note that “a gradual downward trend is evident from an average of ~4.1 (1775-1785) to ~1.5 major hurricanes [per year] during the late 1960s to early 1990s,” and that “the current active phase (1995-2005) is unexceptional compared to the other high-activity periods of ~1756-1774, 1780-1785, 1801-1812, 1840-1850, 1873-1890 and 1928-1933.” Hence, they concluded that the recent ratcheting up of Atlantic major hurricane activity appears to be simply “a recovery to normal hurricane activity.” And in a commentary on Nyberg *et al.*'s paper, Elsner (2007) states that “the assumption that hurricanes are simply passive responders to climate change should be challenged,” which is what Nyberg *et al.* do in a very convincing manner.

Also noting that “global warming is postulated by some researchers to increase hurricane intensity in the north basin of the Atlantic Ocean,” with the implication that “a warming ocean may increase the frequency, intensity, or timing of storms of tropical origin that reach New York State,” Vermette (2007) employed the Historical Hurricane Tracks tool of the National Oceanic and Atmospheric Administration's Coastal Service Center to document all Atlantic Basin tropical cyclones that reached New York State between 1851 and 2005, in order to assess the degree of likelihood that 20<sup>th</sup>-century global warming might be influencing these storms -- as climate alarmists are suggesting it should -- particularly for hurricanes but also for tropical storms, tropical depressions and extratropical storms.

This work revealed, in Vermette's words, that “a total of 76 storms of tropical origin passed over New York State between 1851 and 2005,” and that of these storms, 14 were hurricanes, 27 were tropical storms, 7 were tropical depressions and 28 were extratropical storms.” For Long Island, he further reports that “the average frequency of hurricanes and storms of tropical origin (all types) is one in every 11 years and one in every 2 years, respectively.” Also of note is his finding that storm activity was greatest in *both* the late 19<sup>th</sup> century and the late 20<sup>th</sup> century, and the fact that “the frequency and intensity of storms in the late 20<sup>th</sup> century are similar to those of the late 19<sup>th</sup> century.” As a result, Vermette concludes that “rather than a linear change, that may be associated with a global warming, the changes in recent time are following a multidecadal cycle and returning to conditions of the latter half of the 19<sup>th</sup> century.” Hence, he also concludes that “yet unanswered is whether a warmer global climate of the future will take hurricane activity beyond what has been experienced in the observed record.”

In a similar study, Mock (2008) developed a “unique documentary reconstruction of tropical cyclones for Louisiana, U.S.A. that extends continuously back to 1799 for tropical cyclones, and to 1779 for hurricanes.” This record -- which was derived from daily newspaper accounts, private diaries, plantation diaries, journals, letters and ship records, and which was augmented “with the North Atlantic hurricane database as it pertains to all Louisiana tropical cyclones up through 2007” -- is, in Mock’s words, “the longest continuous tropical cyclone reconstruction conducted to date for the United States Gulf Coast.” And this record reveals that “the 1820s/early 1830s and the early 1860s are the most active periods for the entire record.”

In discussing his findings, the University of South Carolina researcher says that “the modern records which cover just a little over a hundred years is too short to provide a full spectrum of tropical cyclone variability, both in terms of frequency and magnitude.” In addition, he states that “if a higher frequency of major hurricanes occurred in the near future in a similar manner as the early 1800s or in single years such as in 1812, 1831, and 1860, [they] would have devastating consequences for New Orleans, perhaps equaling or exceeding the impacts such as in hurricane Katrina in 2005.” And, of course, the new record clearly indicates that the planet’s current high levels of both air temperature and CO<sub>2</sub> concentration cannot be blamed for the 2005 Katrina catastrophe, as both parameters were much *lower* than they are currently when tropical cyclone and hurricane activity in that region were much *higher* than they are now back in the early to mid 1800s.

Around the same time, Wang and Lee (2008) used the “improved extended reconstructed” *sea surface temperature* (SST) data described by Smith and Reynolds (2004) for the period 1854-2006 to examine historical temperature changes over the global ocean, after which they regressed vertical wind shear -- “calculated as the magnitude of the vector difference between winds at 200 mb and 850 mb during the Atlantic hurricane season (June to November), using NCEP-NCAR reanalysis data” -- onto a temporal variation of global warming defined by the SST data. This work led to their discovery that warming of the surface of the global ocean is typically associated with a secular increase of tropospheric vertical wind shear in the *main development region* (MDR) for Atlantic hurricanes, and that the long-term increased wind shear of that region has coincided with a weak but robust downward trend in U.S. landfalling hurricanes. However, this relationship has a *pattern* to it, whereby local ocean warming in the Atlantic MDR actually *reduces* the vertical wind shear there, while “warmings in the tropical Pacific and Indian Oceans produce an opposite effect, i.e., they increase the vertical wind shear in the MDR for Atlantic hurricanes.”

In light of these findings, the two researchers conclude that “the tropical oceans compete with one another for their impacts on the vertical wind shear over the MDR for Atlantic hurricanes,” and they say that to this point in time, “warmings in the tropical Pacific and Indian Oceans win the competition and produce increased wind shear which reduces U.S. landfalling hurricanes.” As for the years and decades ahead, they write that “whether future global warming increases the vertical wind shear in the MDR for Atlantic hurricanes will depend on the relative role induced by secular warmings over the tropical oceans.” Hence, it is by no means clear whether further global warming, due to *any* cause, will lead to an increase or decrease in U.S. landfalling

hurricanes. All we can say is that up to *this* point in time, global warming appears to have had a weak negative impact on their numbers.

Publishing concurrently, Vecchi and Knutson (2008) write in the introduction to their study of the subject that “there is currently disagreement within the hurricane/climate community on whether anthropogenic forcing (greenhouse gases, aerosols, ozone depletion, etc.) has caused an increase in Atlantic tropical storm or hurricane frequency.” In further exploring this question, they derived an estimate of the expected number of North Atlantic tropical cyclones (TCs) that were missed by the observing system in the pre-satellite era (1878-1965), after which they analyzed trends of both reconstructed TC *numbers* and *duration* over various time periods and looked at how they may or may not have been related to trends in sea surface temperature over the main development region of North Atlantic TCs. This work revealed, in their words, that “the estimated trend for 1900-2006 is highly significant ( $+4.2$  storms century<sup>-1</sup>),” but they say that the trend “is strongly influenced by a minimum in 1910-30, perhaps artificially enhancing significance.” When using their base case adjustment for missed TCs and considering the entire 1878-2006 record, for example, they find that the trend in the *number* of TCs is only “weakly positive” and “not statistically significant,” while they note that the trend in average TC *duration* over the 1878-2006 period “is negative and highly significant.”

In conclusion, the bulk of the evidence that has been accumulated to date over multi-century timescales indicates that late 20<sup>th</sup>-century yearly hurricane numbers were considerably lower than those observed in colder prior centuries, verifying what Elsner (2008) wrote in his summary of the *International Summit on Hurricanes and Climate Change* that was held in May of 2007 on the Greek island of Crete, wherein he states that *paleotempestology* -- which he defines as the study of prehistoric storms based on geological and biological evidence -- indicates the presence of more hurricanes in the northeastern Caribbean Sea “during the second half of the Little Ice Age when sea temperatures near Puerto Rico were a few degrees (Celsius) cooler than today,” which he goes on to say provides evidence that “today’s warmth is not needed for increased storminess.”

Indeed, it is not. And there is no compelling reason to believe that any additional warmth that may come our way would be any different.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/h/hurratlancent.php>.

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#### 5.3.1.2.3. THE PAST CENTURY

Have tropical storms and hurricanes of the Atlantic Ocean become more numerous over the past century, in response to what climate alarmists describe as unprecedented global warming?

In an attempt to answer this question, Bove *et al.* (1998) examined the characteristics of all recorded landfalling U.S. Gulf Coast hurricanes -- defined as those whose eyes made landfall between Cape Sable, Florida and Brownsville, Texas -- from 1896 to 1995. In doing so, they found that the first half of this period saw considerably more hurricanes than the last half: 11.8 per decade vs. 9.4 per decade, while the same was true for intense hurricanes of category 3 or more on the Saffir-Simpson storm scale: 4.8 vs. 3.6. In fact, the numbers of all hurricanes and the numbers of intense hurricanes both tended downward from 1966 to the end of the period investigated, with the decade 1986-1995 exhibiting the fewest intense hurricanes of the entire century. Hence, the three researchers concluded that "fears of increased hurricane activity in the Gulf of Mexico are premature."

Noting that the 1995 Atlantic hurricane season was one of near-record tropical storm and hurricane activity, but that during the preceding four years (1991-94) such activity over the Atlantic basin was the lowest since the keeping of reliable records began in the mid-1940s, Landsea *et al.* (1998) studied the meteorological characteristics of the two periods to determine what might have caused the remarkable upswing in storm activity in 1995. In doing so, they found that "perhaps the primary factor for the increased hurricane activity during 1995 can be

attributed to a favorable large-scale pattern of extremely low vertical wind shear throughout the main development region." They also noted that "in addition to changes in the large-scale flow fields, the enhanced Atlantic hurricane activity has also been linked to below-normal sea level pressure, abnormally warm ocean waters, and very humid values of total precipitable water."

An additional factor that may have contributed to the enhanced activity of the 1995 Atlantic hurricane season was the westerly phase of the stratospheric quasi-biennial oscillation, which is known to enhance Atlantic basin storm activity. Possibly the most important factor of all, however, was what Landsea *et al.* called the "dramatic transition from the prolonged late 1991-early 1995 warm episode (El Niño) to cold episode (La Niña) conditions," which contributed to what they described as "the dramatic reversal" of weather characteristics "which dominated during the [prior] four hurricane seasons."

"Some have asked," in the words of the four researchers, "whether the increase in hurricanes during 1995 is related to the global surface temperature increases that have been observed over the last century, some contribution of which is often ascribed to increases in anthropogenic 'greenhouse' gases." In reply, they stated that "such an interpretation is not warranted," because the various factors noted above seem sufficient to explain the observations. "Additionally," as they further wrote, "Atlantic hurricane activity has actually decreased significantly in both frequency of intense hurricanes and mean intensity of all named storms over the past few decades," and "this holds true even with the inclusion of 1995's Atlantic hurricane season."

In a major synthesis of Atlantic basin hurricane indices published the following year, Landsea *et al.* (1999) reported long-term variations in tropical cyclone activity for this region (North Atlantic Ocean, Gulf of Mexico, and Caribbean Sea). Over the period 1944-1996, decreasing trends were found for (1) the total number of hurricanes, (2) the number of intense hurricanes, (3) the annual number of hurricane days, (4) the maximum attained wind speed of all hurricane storms averaged over the course of a year, and (5) the highest wind speed associated with the strongest hurricane recorded in each year. In addition, they reported that the total number of Atlantic hurricanes making landfall in the United States had decreased over the 1899-1996 time period, and that *normalized* trends in hurricane damage in the United States between 1925 and 1996 revealed such damage to be decreasing at a rate of 728 million dollars per decade.

In a similar study that included a slightly longer period of record (1935-1998), Parisi and Lund (2000) conducted a number of statistical tests on all Atlantic Basin hurricanes that made landfall in the contiguous United States, finding that "a simple linear regression of the yearly number of landfalling hurricanes on the years of study produces a trend slope estimate of  $-0.011 \pm 0.0086$  storms per year." And to drive home the significance of that result, they expressly called attention to the fact that "the estimated trend slope is negative," which means, of course, that -- *if anything* -- the yearly number of such storms is *decreasing*, which is just the *opposite* of what they described as the "frequent hypothesis ... that global warming is causing

increased storm activity." Their statistical analysis, however, indicates that "the trend slope is not significantly different from zero."

Contemporaneously, Easterling *et al.* (2000) noted that the mean temperature of the globe rose by about 0.6°C over the past century; and they thus looked for possible impacts of this phenomenon on extreme weather events, which if found to be increasing, as they describe it, "would add to the body of evidence that there is a discernable human affect on the climate." Their search, however, revealed few changes of significance, although they did determine that "the number of intense and landfalling Atlantic hurricanes has *declined* [our italics]."

Three years later, Balling and Cervený (2003) wrote that "many numerical modeling papers have appeared showing that a warmer world with higher sea surface temperatures and elevated atmospheric moisture levels could increase the frequency, intensity, or duration of future tropical cyclones," but that empirical studies had failed to reveal any such relationships. They also noted that "some scientists have suggested that the buildup of greenhouse gases can ultimately alter other characteristics of tropical cyclones, ranging from timing of the active season to the location of the events," and that these relationships have *not* been thoroughly studied with historical real-world data. Hence, they proceeded to fill this void by conducting such a study for tropical storms in the Caribbean Sea, the Gulf of Mexico, and the western North Atlantic Ocean.

More specifically, the two Arizona State University climatologists constructed a daily database of tropical storms that occurred within their study area over the period 1950-2002, generating "a variety of parameters dealing with duration, timing, and location of storm season," after which they tested for trends in these characteristics, attempting to explain the observed variances in the variables using regional, hemispheric and global temperatures. In doing so, they report they "found no trends related to timing and duration of the hurricane season and geographic position of storms in the Caribbean Sea, Gulf of Mexico and tropical sector of the western North Atlantic Ocean." Likewise, they said they "could find no significant trends in these variables and generally no association with them and the local ocean, hemispheric, and global temperatures."

Elsner *et al.* (2004) conducted a *change point analysis* of time series of annual major North Atlantic hurricane counts and annual major U.S. hurricane counts for the 20<sup>th</sup> century, which technique, in their words, "quantitatively identifies temporal shifts in the mean value of the observations." This work revealed that "major North Atlantic hurricanes have become more frequent since 1995," but at "a level reminiscent of the 1940s and 1950s." In actuality, however, they had not quite reached that level, nor had they maintained it for as long a time. Their data indicate, for example, that the mean annual hurricane count for the 7-year period 1995-2001 was 3.86, while the mean count for the 14-year period 1948-1961 was 4.14. They also reported that, "in general, twentieth-century U.S. hurricane activity shows no abrupt shifts," noting, however, that there was an exception over Florida, "where activity decreased during the early 1950s and again during the late 1960s." Last of all, they found that "El Niño

events tend to suppress hurricane activity along the entire coast with the most pronounced effects over Florida.”

In contradiction of the oft-stated claim that global warming leads to more intense hurricane activity, the results of Elsner *et al.*'s study clearly suggest otherwise. Not only did North Atlantic hurricane activity *not* increase over the *entire 20th century*, during which period climate alarmists say the earth experienced a temperature increase that was *unprecedented over the past two millennia*, hurricane activity also did not increase in response to the more sporadic warming associated with periodic El Niño conditions. In fact, it *decreased*.

Two years later, things got a bit more interesting. “The 2005 hurricane season,” in the words of Virmani and Weisberg (2006), “saw an unprecedented number of named tropical storms since records began in 1851.” Moreover, they said it followed “on the heels of the unusual 2004 hurricane season when, in addition to the first South Atlantic hurricane, a record-breaking number of major hurricanes made landfall in the United States, also causing destruction on the Caribbean islands in their path.” The question they thus posed for themselves was whether these things occurred in response to recent global warming or if they bore sufficient similarities with hurricane seasons of years past to preclude such an attribution.

In probing this question the two researchers determined that “latent heat loss from the tropical Atlantic and Caribbean was less in late spring and early summer 2005 than preceding years due to anomalously weak trade winds associated with weaker sea level pressure,” which phenomenon “resulted in anomalously high sea surface temperatures” that “contributed to earlier and more intense hurricanes in 2005.” However, they went on to note that “these conditions in the Atlantic and Caribbean during 2004 and 2005 were not unprecedented and were equally favorable during the active hurricane seasons of 1958, 1969, 1980, 1995 and 1998.” In addition, they said there was “not a clear link between the Atlantic Multidecadal Oscillation or the long term trend [of temperature] and individual active hurricane years, confirming the importance of other factors in hurricane formation.” Hence, it would appear that the 2005 hurricane season was not as unique as many people have made it out to be, and that there is no compelling reason to ascribe whatever degree of uniqueness it may have possessed to recent global warming.

By the time three more years had elapsed, however, Mann and Emanuel (2006) had used quantitative records stretching back to the mid-nineteenth century to develop a positive correlation between sea surface temperatures and Atlantic basin tropical cyclone frequency for the period 1871-2005, while Holland and Webster (2007) had analyzed Atlantic tropical cyclone frequency back to 1855 and found a doubling of the number of tropical cyclones over the past 100 years; and both of these papers linked these changes to anthropogenic greenhouse warming. In a compelling rebuttal of these conclusions, however, Landsea (2007) cited a number of possible biases that may exist in the cyclone frequency trends derived in the two studies, concluding that “improved monitoring in recent years is responsible for most, if not all, of the observed trend in increasing frequency of tropical cyclones.”

Most recently, Parisi and Lund (2008) calculated return periods of Atlantic-basin U.S. landfalling hurricanes based on “historical data from the 1900 to 2006 period via extreme value methods and Poisson regression techniques” for each of the categories (1-5) of the Saffir-Simpson Hurricane Scale. This work revealed that return periods (in years) for these hurricanes were, in ascending Saffir-Simpson Scale category order: (1) 0.9, (2) 1.3, (3) 2.0, (4) 4.7, and (5) 23.1. In addition, the two researchers reported that corresponding non-encounter probabilities in any one hurricane season were calculated to be (1) 0.17, (2) 0.37, (3) 0.55, (4) 0.78, and (5) 0.95; and they stated that the *hypothesis* that U.S. hurricane strike frequencies are “increasing in time” -- which is often stated as fact by climate alarmists -- is “statistically rejected.”

In light of the long history of multi-decadal to century-scale analyses that have come to the same conclusion, we must reject the oft-spoken claim that Atlantic hurricanes have increased in frequency in response to 20<sup>th</sup>-century global warming.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/h/hurratlangwe.php>.

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#### 5.3.1.2.4. THE EL NIÑO EFFECT

How does the frequency of occurrence of Atlantic basin hurricanes respond to increases in temperature? In exploring this important question within the context of the warming that occurs in going from La Niña conditions to El Niño conditions, Wilson (1999) utilized data from the last half of the 20th century in determining that the probability of having three or more intense hurricanes was only 14% during an El Niño year, but fully 53% during a La Niña year. Hence, the probability of experiencing three or more intense Atlantic basin hurricanes when going from a cooler La Niña year to a warmer El Niño year actually drops, from a hefty 53% to a mere 14%, or to only about a quarter of what the probability of occurrence was before the temperature increase occurred.

Muller and Stone (2001) conducted a similar study of tropical storm and hurricane strikes along the southeast U.S. coast from South Padre Island (Texas) to Cape Hatteras (North Carolina), using data from the entire past century. For tropical storms and hurricanes together, they found an average of 3.3 strikes per La Niña season, 2.6 strikes per neutral season, and 1.7 strikes per El Niño season. For hurricanes alone, the average rate of strike occurrence ranged from 1.7 per La Niña season to 0.5 per El Niño season, which represents a frequency-of-occurrence decline of fully 70% in going from cooler La Niña conditions to warmer El Niño conditions. Likewise, Elsner *et al.* (2001) - who also worked with data from the entire past century - found that when there are below normal sea surface temperatures in the equatorial Pacific, "the probability of a U.S. hurricane increases."

Lyons (2004) also conducted a number of analyses of U.S. landfalling tropical storms and hurricanes, dividing them into three different groupings: the 10 highest storm and hurricane landfall years, the 9 lowest such years, and all other years. These groupings revealed, in Lyons' words, that "La Niña conditions occurred 19% more often during high U.S. landfall years than during remaining years," and that "El Niño conditions occurred 10% more often during low U.S. landfall years than during remaining years." In addition, it was determined that "La Niña (El

Niño) conditions were 18% (25%) more frequent during high (low) U.S. landfall years than during low (high) U.S. landfall years."

An analogous approach was used by Pielke and Landsea (1999) to study the effect of warming on the intensity of Atlantic basin hurricanes, using data from the period 1925 to 1997. In their analysis, they first determined that 22 years of this period were El Niño years, 22 were La Niña years, and 29 were neither El Niño nor La Niña years. Then, they compared the average hurricane wind speed of the cooler La Niña years with that of the warmer El Niño years, finding that in going from the cooler climatic state to the warmer climatic state, average hurricane wind speed dropped by about 6 meters per second.

Independent confirmation of these findings was provided by Pielke and Landsea's assessment of concurrent hurricane damage in the United States: El Niño years experienced only half the damage of La Niña years. And in a ten-year study of a Mediterranean waterbird (Cory's Shearwater) carried out on the other side of the Atlantic, Brichetti *et al.* (2000) determined - contrary to their own expectation - that survival rates during warmer El Niño years were actually greater than during cooler La Niña years.

In another pertinent study, Landsea *et al.* (1998) analyzed the meteorological circumstances associated with the development of the 1995 Atlantic hurricane season, which was characterized by near-record tropical storm and hurricane activity after four years (1991-94) that had exhibited the lowest such activity since the keeping of reliable records began. They determined that the most important factor behind this dramatic transition from extreme low to extreme high tropical storm and hurricane activity was what they called the "dramatic transition from the prolonged late 1991-early 1995 warm episode (El Niño) to cold episode (La Niña) conditions."

Last of all, in a 20th century change point analysis of time series of major North Atlantic and U.S. annual hurricane counts, which in the words of its authors, "quantitatively identifies temporal shifts in the mean value of the observations," Elsner *et al.* (2004) found that "El Niño events tend to suppress hurricane activity along the entire coast with the most pronounced effects over Florida."

The obvious conclusion to be drawn from the results of these several studies, which is clearly contrary to that espoused by the majority of the world's climate alarmists, is that global warming does not lead to either more frequent or more intense Atlantic basin hurricanes. In fact, it generally does just the opposite. Nevertheless, some scientists continue to ignore these real-world facts, content instead to place their faith in the tenuous output of theoretical climate models.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/h/hurratlanelnino.php>.

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### 5.3.2. Indian Ocean

Singh *et al.* (2000, 2001) analyzed 122 years of tropical cyclone data from the North Indian Ocean over the period 1877-1998. Since this was the period of time during which the planet recovered from the global chill of the Little Ice Age, it is logical to assume that their findings would be indicative of changes in hurricane characteristics we might expect if the earth were to warm by that amount again, which is what climate alarmists are almost promising us it will do.

So, what did Singh *et al.* find? On an annual basis, there was a slight *decrease* in tropical cyclone frequency, such that the North Indian Ocean, on average, experienced about one *less* hurricane per year at the end of the 122-year record in 1998 than it did at its start in 1877. In addition, based on data from the Bay of Bengal, they found that tropical cyclone numbers *dropped* during the months of most *severe* cyclone formation (November and May), when the El Niño-Southern Oscillation was in a *warm* phase. In light of these real-world observations, it would thus appear that if tropical cyclones of the North Indian Ocean were to change *at all* in response to global warming, their overall frequency and the frequency of the most intense such



storms would likely *decrease*, which is just the opposite of what climate alarmists typically claim will occur.

Hall (2004) analyzed characteristics of cyclones occurring south of the equator from longitude 90°E to 120°W in the South Pacific and southeast Indian Oceans, concentrating on the 2001-2002 cyclone season and comparing the results with those of the preceding four years and the 36 years before that. This work revealed that "the 2001-2002 tropical cyclone season in the South Pacific and southeast Indian Ocean was one of the quietest on record, in terms of both the number of cyclones that formed, and the impact of those systems on human affairs." In the southeast Indian Ocean, for example, Hall determined that "the overall number of depressions and tropical cyclones was below the long-term mean." Further east, he found that broad-scale convection was near or slightly above normal, but that "the proportion of tropical depressions and weak cyclones developing into severe cyclones was well below average," which result represented "a continuation of the trend of the previous few seasons." What is more, Hall writes that "in the eastern Australian region, the four-year period up to 2001-2002 was by far the quietest recorded in the past 41 years." Consequently, Hall's work too, like that of Singh *et al.*, suggests a likely *decline* in both the intensity and frequency of Indian-Ocean tropical cyclones if the world continues to warm.

Raghavan and Rajesh (2003) reviewed the general state of scientific knowledge relative to trends in the frequency and intensity of tropical cyclones throughout the world, giving special attention to the Indian state of Andhra Pradesh, which borders on the Bay of Bengal. For the North Indian Ocean (NIO), comprising both the Bay of Bengal and the Arabian Sea, they report that for the period 1891-1997 there was a significant *decreasing* trend (at the 99% confidence level) in the frequency of cyclones with the designation of "cyclonic storm" and above, and that "the maximum decrease was in the last four decades," citing the work of Srivastava *et al.* (2000). In addition, they note that Singh and Khan (1999), who studied 122 years of data, also found the annual frequency of NIO-basin tropical cyclones to be decreasing.

As in other parts of the world, however, they found increasing *impacts* of tropical cyclones; but their economic analysis led them to conclude that "increasing damage due to tropical cyclones over Andhra Pradesh, India, is attributable mainly to economic and demographic factors and not to any increase in frequency or intensity of cyclones." Hence, and with no equivocation, they state that "inflation, growth in population, and the increased wealth of people in the coastal areas (and not global warming) are the factors contributing to the increased impact."

Commenting on their findings, the researchers say "there is a common perception in the media, and even government and management circles, that [increased property damage from tropical cyclones] is due to an increase in tropical cyclone frequency and perhaps in intensity, probably as a result of global climate change." However, as they continue, "studies all over the world show that though there are decadal variations, there is no definite long-term trend in the frequency or intensity of tropical cyclones." Hence, they confidently state that "the specter of tropical cyclones increasing alarmingly due to global climate change, portrayed in the popular

media and even in some more serious publications, does not therefore have a sound scientific basis," which pretty much obviates the need for us to say anything further about the topic.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/h/hurricaneindian.php>.

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### 5.3.3. Pacific Ocean

Free *et al.* (2004) note that "increases in hurricane intensity are expected to result from increases in sea surface temperature and decreases in tropopause-level temperature accompanying greenhouse warming (Emanuel, 1987; Henderson-Sellers *et al.*, 1998; Knutson *et al.*, 1998)." In fact, Knutson and Tuleya (2004) state that "nearly all combinations of climate model boundary conditions and hurricane model convection schemes show a CO<sub>2</sub>-induced increase in both storm intensity and near-storm precipitation rates." Hence, it is only natural to wonder how much more frequent and powerful hurricanes might have become since earth's recovery from the cooler temperatures of the Little Ice Age. In this section, we explore this question via a review of pertinent studies pertaining to the Pacific Ocean.

Chu and Clark (1999) analyzed the frequency and intensity of tropical cyclones that either originated in or entered the central North Pacific (0-70°N, 140-180°W) over the 32-year period 1966-1997. After doing so, they determined that "tropical cyclone activity (tropical depressions, tropical storms, and hurricanes combined) in the central North Pacific [was] on the rise." This increase, however, appears to have been due to a *step-change* that led to the creation of

"fewer cyclones during the first half of the record (1966-81) and more during the second half of the record (1982-1997)," and accompanying the abrupt rise in tropical cyclone numbers was a similar abrupt increase in maximum hurricane intensity.

Although climate alarmists may claim these findings support their model-based contentions, i.e., that CO<sub>2</sub>-induced global warming leads to more frequent and stronger hurricanes, Chu and Clark say that the observed increase in tropical cyclone activity *cannot* be due to CO<sub>2</sub>-induced global warming, because, in their words, "global warming is a gradual processes" and "it cannot explain why there is a steplike change in the tropical cyclone incidences in the early 1980s."

Clearly, a much longer record of tropical cyclone activity is needed to better understand the nature of the variations documented by Chu and Clark, as well as their relationship to mean global air temperature; and the beginnings of such a history were presented by Liu *et al.* (2001), who meticulously waded through a wealth of weather records from Guangdong Province in southern China, extracting data pertaining to the landfall of typhoons there since AD 975. Calibrating the historical data against instrumental observations over the period 1884-1909, they found the trends of the two data sets to be significantly correlated ( $r = 0.71$ ). This observation led them to conclude that "the time series reconstructed from historical documentary evidence contains a reliable record of variability in typhoon landfalls." Hence, they proceeded to conduct a spectral analysis of the Guangdong time series and discovered an approximate 50-year cycle in the frequency of typhoon landfall that "suggests an external forcing mechanism, which remains to be identified." Also, and very importantly, they found that "the two periods of most frequent typhoon strikes in Guangdong (AD 1660-1680, 1850-1880) coincide with two of the coldest and driest periods in northern and central China during the Little Ice Age."

Looking even further back in time into the Southern Hemisphere, Hayne and Chappell (2001) studied a series of storm ridges at Curacoa Island, which were deposited over the past 5,000 years on the central Queensland shelf (18°40'S; 146°33'E), in an attempt to create a long-term history of major cyclonic events that have impacted that area, with one of their stated reasons for doing so being to test the climate-model-based hypothesis that "global warming leads to an increase of cyclone frequency or intensity." The primary finding of this endeavor, as they describe it, was that "cyclone frequency was statistically constant over the last 5,000 years." In addition, they could find "no indication that cyclones have changed in intensity," leaving one little to conclude but that the climate-model-based hypothesis is inconsistent with their findings.

In a similar study, Nott and Hayne (2001) produced a 5000-year record of tropical cyclone frequency and intensity along a 1500-km stretch of coastline in northeast Australia located between latitudes 13 and 24°S by geologically dating and topographically surveying landform features left by historic hurricanes, and running numerical models to estimate storm surge and wave heights necessary to reach the landform locations. These efforts revealed that several "super-cyclones" with central pressures less than 920 hPa and wind speeds in excess of 182 kilometers per hour had occurred over the past 5000 years at intervals of roughly 200 to 300

years in all parts of the region of their study. They also report that the Great Barrier Reef "experienced at least five such storms over the past 200 years, with the area now occupied by Cairns experiencing two super-cyclones between 1800 and 1870." The 20th century, however, which is claimed by climate alarmists to have experienced temperatures that were *unprecedented over the past two millennia*, was *totally devoid* of such storms, "with only one such event (1899) since European settlement in the mid-nineteenth century."

Also noting that "many researchers have suggested that the buildup of greenhouse gases (Watson *et al.*, 2001) will likely result in a rise in sea surface temperature (SST), subsequently increasing both the number and maximum intensity of tropical cyclones (TCs)," Chan and Liu (2004) explored the validity of this assertion via an examination of pertinent real-world data *because*, as they put it, "if the frequency of TC occurrence were to increase with increasing global air temperature, one would expect to see an increase in the number of TCs during the past few decades." Their efforts, which focused on the last four decades of the 20th century, resulted in their finding that a number of parameters related to SST and TC activity in the Western North Pacific (WNP) "have gone through large interannual as well as interdecadal variations," and that "they also show a slight *decreasing* [our italics] trend." In addition, they say that "no significant correlation was found between the typhoon activity parameters and local SST," or "in other words," as they say to drive home their point, "an increase in local SST does not lead to a significant change of the number of intense TCs in the WNP, which is contrary to the results produced by many of the numerical climate models." Instead, they found that "the interannual variation of annual typhoon activity is mainly constrained by the ENSO phenomenon through the alteration of the large-scale circulation induced by the ENSO event."

In discussing their results, Chan and Liu write that the reason for the discrepancies between their real-world results and those of many of the numerical climate models likely lies in the fact that the models assume TCs are generated primarily from energy from the oceans and that a higher SST therefore would lead to more energy being transferred from the ocean to the atmosphere, or "in other words," as they once again say in striving to make their point as clear as possible, "the typhoon activity predicted in these models is almost solely determined by thermodynamic processes, as advocated by Emanuel (1999)," whereas "in the real atmosphere, dynamic factors, such as the vertical variation of the atmospheric flow (vertical wind shear) and the juxtaposition of various flow patterns that lead to different angular momentum transports, often outweigh the thermodynamic control in limiting the intensification process." Their final conclusion, therefore, is that "at least for the western North Pacific, observational evidence does not support the notion that increased typhoon activity will occur with higher local SSTs."

Much the same thing was found by Free *et al.* (2004), who looked, not for increases in *actual* hurricane intensity, but for increases in *potential* hurricane intensity, because, as they put it, "changes in potential intensity (PI) can be estimated from thermodynamic principles as shown in Emanuel (1986, 1995) given a record of SSTs and profiles of atmospheric temperature and humidity." This they did using radiosonde and SST data from 14 island radiosonde stations in both the tropical Pacific *and* Atlantic Oceans, after which they compared their results with

those of Bister and Emanuel (2002) at grid points near the selected stations. In doing so, they report that their results showed "no significant trend in potential intensity from 1980 to 1995 and no consistent trend from 1975 to 1995." What is more, they report that between 1975 and 1980, "while SSTs rose, PI decreased, illustrating the hazards of predicting changes in hurricane intensity from projected SST changes alone."

Hall (2004) reviewed the characteristics of cyclones occurring south of the equator and eastward from longitude 90°E to 120°W in the South Pacific and southeast Indian Oceans, concentrating on the 2001-2002 cyclone season and comparing the results with those of the preceding four years and the 36 years before that. This analysis indicated that "the 2001-2002 tropical cyclone season in the South Pacific and southeast Indian Ocean was one of the quietest on record, in terms of both the number of cyclones that formed, and the impact of those systems on human affairs." In the southeast Indian Ocean, for example, he writes that "the overall number of depressions and tropical cyclones was below the long-term mean," while further east he found that broad-scale convection was near or slightly above normal, but that "the proportion of tropical depressions and weak cyclones developing into severe cyclones was well below average," which result represented "a continuation of the trend of the previous few seasons." More specifically, Hall writes that "in the eastern Australian region, the four-year period up to 2001-2002 was *by far* [our italics] the quietest recorded in the past 41 years." Consequently, and in stark contrast to the climate-alarmist claim that tropical cyclone numbers and strength tend to increase with global warming, these real-world observations suggest that, if anything, just the opposite appears to be occurring.

Noting that "according to Walsh and Ryan (2000), future global climate trends may result in an increased incidence of cyclones," and realizing that "understanding the behavior and frequency of severe storms in the past is crucial for the prediction of future events," Yu *et al.* (2004) devised a way to decipher the history of severe storms in the southern South China Sea. Working at Youngshu Reef (9°32'-9°42'N, 112°52' -113°04'E), they used standard radiocarbon dating together with TIMS U-series dating to determine the times of occurrence of storms that were strong enough to actually "relocate" large *Porites* coral blocks that are widespread on the reef flats there. This program revealed that "during the past 1000 years, at least six exceptionally strong storms occurred," which they dated to approximately AD 1064 ± 30, 1218 ± 5, 1336 ± 9, 1443 ± 9, 1682 ± 7 and 1872 ± 15, yielding an average recurrence time of 160 years. Interestingly, *none* of these six severe storms occurred during the past millennium's last century, which climate alarmists claim was the warmest such period of that thousand-year interval.

Noting that Emanuel (2005) and Webster *et al.* (2005) have claimed that "tropical cyclone intensity has increased markedly in recent decades," and saying that because they specifically argued that "tropical cyclone activity over the western North Pacific has been changed in response to the ongoing global warming," Ren *et al.* (2006) decided to see if any increases in tropical cyclone activity had occurred over China between 1957 and 2004. This they did by analyzing tropical cyclone (TC) precipitation (P) data from 677 Chinese weather stations for the period 1957 to 2004, searching for evidence of long-term changes in TCP and TC-induced

torrential precipitation events. Interestingly, this search indicated, in their words, that "significant *downward* [our italics] trends are found in the TCP volume, the annual frequency of torrential TCP events, and the contribution of TCP to the annual precipitation over the past 48 years." Also, they say that the downward trends were accompanied by "decreases in the numbers of TCs and typhoons that affected China during the period 1957-2004." In a conclusion that consequently differs dramatically from the claims of Emanuel (2005) and Webster *et al.* (2005) relative to inferred increases in tropical cyclone activity over the western North Pacific in recent decades, Ren *et al.* say their findings "*strongly* [our italics] suggest that China has experienced *decreasing* [our italics] TC influence over the past 48 years, especially in terms of the TCP."

Nott *et al.* (2007) developed a 777-year-long annually-resolved record of landfalling tropical cyclones in northeast Australia based on analyses of isotope records of tropical cyclone rainfall in an annually-layered carbonate stalagmite from Chillagoe (17.2°S, 144.6°E) in northeast Queensland. Perhaps their most important discovery in doing so was their finding that "the period between AD 1600 to 1800" -- when the Little Ice Age held sway throughout the world -- "had many more intense or hazardous cyclones impacting the site than the post AD 1800 period," when the planet gradually began to warm at a rate that rose to ultimately become what climate alarmists characterize as *unprecedented over the past millennium or more*, and when temperatures rose to a level they claim was equally unprecedented. In harmony with the four researchers' feeling that "the only way to determine the likely future behavior of tropical cyclones is to first understand their history from high resolution records of multi-century length or greater," which is only common sense, it would thus appear that claims such as those of Emanuel (2005) and Webster *et al.* (2005) are lacking in real-world support from this region as well as many areas throughout the Pacific Ocean.

Last of all, Li *et al.* (2007) analyzed real-world tropical cyclone data pertaining to the western North Pacific basin archived in the *Yearbook of Typhoon* published by the China Meteorological Administration for the period 1949-2003, together with contemporaneous atmospheric information obtained from the National Center for Environmental Protection reanalysis dataset for the period 1951-2003. Following this endeavor, they used their empirical findings to infer future tropical cyclone activity in the region based upon climate-model simulations of the state of the general circulation of the atmosphere over the next half-century. This protocol revealed, first of all, that there were "more tropical cyclones generated over the western North Pacific from the early 1950s to the early 1970s in the 20th century and less tropical cyclones from the mid-1970s to the present." They further found that "the decadal changes of tropical cyclone activities are closely related to the decadal changes of atmospheric general circulation in the troposphere, which provide favorable or unfavorable conditions for the formation of tropical cyclones." Based on simulations of future occurrences of these favorable and unfavorable conditions derived from "a coupled climate model under the [A2 and B2] schemes of the Intergovernmental Panel on Climate Change special report on emission scenarios," they then determined that "the general circulation of the atmosphere would become unfavorable for the formation of tropical cyclones as a whole and the frequency of tropical cyclone formation

would likely decrease by 5% within the next half century, although more tropical cyclones would appear during a short period of it."

In light of these several sets of *hard evidence* from the *real world of nature*, as opposed to the *theoretical constructs* from the *virtual world of climate models*, it would appear that the climatic implications of the two worlds are *worlds apart from each other*.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/h/hurricanepacific.php>.

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### 5.3.4. Global

Although some climate models suggest the intensity and frequency of tropical cyclones may be significantly reduced in response to global warming (Bengtsson *et al.*, 1996), thus implying a "decrease in the global total number of tropical cyclones on doubling CO<sub>2</sub>," as noted by Sugi *et al.* (2002), most of them suggest otherwise, as noted by Free *et al.* (2004), who state that "increases in hurricane intensity are expected to result from increases in sea surface temperature and decreases in tropopause-level temperature accompanying greenhouse warming (Emanuel, 1987; Henderson-Sellers *et al.*, 1998; Knutson *et al.*, 1998)." Hence, it is important to see what the world of nature has to say about the issue.

In an early review of empirical evidence related to the subject, Walsh and Pittock (1998) concluded that "the effect of global warming on the number of tropical cyclones is presently unknown," and that "there is little relationship between SST (sea surface temperature) and tropical cyclone numbers in several regions of the globe." Hence, they opined there was "little evidence that changes in SSTs, by themselves, could cause change in tropical cyclone numbers."

In a second early analysis of the topic, Henderson-Sellers *et al.* (1998) determined that (1) "there are no discernible global trends in tropical cyclone number, intensity, or location from historical data analyses," (2) "global and mesoscale-model-based predictions for tropical cyclones in greenhouse conditions have not yet demonstrated prediction skill," and (3) "the popular belief that the region of cyclogenesis will expand with the 26°C SST isotherm is a fallacy."

Six years later, in yet another futile attempt to find the long-sought global warming signal in hurricane data, Free *et al.* (2004) looked for increases in *potential* hurricane intensity, because, as they put it, "changes in potential intensity (PI) can be estimated from thermodynamic principles as shown in Emanuel (1986, 1995) given a record of SSTs and profiles of atmospheric temperature and humidity." This they thus did, using radiosonde and SST data from 14 island radiosonde stations in the tropical Atlantic and Pacific Oceans, after which they compared their results with those of Bister and Emanuel (2002) at grid points near the selected stations.

So what did they find? As Free *et al.* describe it, "our results show no significant trend in potential intensity from 1980 to 1995 and no consistent trend from 1975 to 1995." What is more, they report that between 1975 and 1980, "while SSTs rose, PI decreased, illustrating the hazards of predicting changes in hurricane intensity from projected SST changes alone." In addition, in another review of what real-world data have to say about the subject, Walsh (2004) was once again forced to report "there is as yet no convincing evidence in the observed record of changes in tropical cyclone behavior that can be ascribed to global warming." Nevertheless, Walsh continued to believe that (1) "there is likely to be some increase in maximum tropical cyclone intensities in a warmer world," (2) "it is probable that this would be accompanied by increases in mean tropical cyclone intensities," and (3) "these increases in intensities are likely to be accompanied by increases in peak precipitation rates of about 25%," putting the date of

possible detection of these increases "some time after 2050," little knowing that *two* such claims would actually be made the *very next year*.

The historic contentions came from Emanuel (2005), who claimed to have found that a hurricane power dissipation index had increased by approximately 50% for both the Atlantic basin and the Northwest Pacific basin since the mid 1970s, and from Webster *et al.* (2005), who contended that the numbers of Category 4 and 5 hurricanes for all tropical cyclone basins had nearly doubled between an earlier (1975-1989) and a more recent (1990-2004) 15-year period. *However*, in a challenge to *both* of these claims, Klotzbach (2006) wrote that "many questions have been raised regarding the data quality in the earlier part of their analysis periods," and he thus proceeded to perform a new analysis based on a "near-homogeneous" *global* data set for the period 1986-2005.

So what did Klotzbach do? And what did he find?

Klotzbach first tabulated global tropical cyclone (TC) activity using *best track data* -- which he describes as "the best estimates of the locations and intensities of TCs at six-hour intervals produced by the international warning centers" -- for all TC basins (North Atlantic, Northeast Pacific, Northwest Pacific, North Indian, South Indian and South Pacific), after which he determined trends of worldwide TC frequency and intensity over the period 1986-2005, during which time global SSTs are purported to have risen by about 0.2-0.4°C. This work did indeed indicate, in his words, "a large increasing trend in tropical cyclone intensity and longevity for the North Atlantic basin," but it also indicated "a considerable decreasing trend for the Northeast Pacific," and combining these observations with the fact that "all other basins showed small trends," he determined there had been "no significant change in global net tropical cyclone activity" over the past two decades. With respect to Category 4 and 5 hurricanes, however, he found there had been a "small increase" in their numbers from the first half of the study period (1986-1995) to the last half (1996-2005); but he noted that "most of this increase is likely due to improved observational technology." Not mincing any words, therefore, Klotzbach declared that his findings were "contradictory to the conclusions drawn by Emanuel (2005) and Webster *et al.* (2005)," in that the global TC data did "not support the argument that global TC frequency, intensity and longevity have undergone increases in recent years."

Following close on the heels of Klotzbach's study came the paper of Kossin *et al.* (2007), who wrote that "the variability of the available data combined with long time-scale changes in the availability and quality of observing systems, reporting policies, and the methods utilized to analyze the data make the best track records inhomogeneous," and stated that this "known lack of homogeneity in both the data and techniques applied in the post-analyses has resulted in skepticism regarding the consistency of the best track intensity estimates." Consequently, as an important first step in resolving this problem, Kossin *et al.* "constructed a more homogeneous data record of hurricane intensity by first creating a new consistently analyzed global satellite data archive from 1983 to 2005 and then applying a new objective algorithm to the satellite data to form hurricane intensity estimates," after which they analyzed the

resultant homogenized data for temporal trends over the period 1984-2004 for all major ocean basins and the global ocean as a whole.

In describing what they learned from this exercise, the five scientists who conducted the work said that "using a homogeneous record, we were not able to corroborate the presence of upward trends in hurricane intensity over the past two decades in any basin other than the Atlantic." Therefore, noting that "the Atlantic basin accounts for less than 15% of global hurricane activity," they concluded that "this result poses a challenge to hypotheses that directly relate globally increasing tropical sea surface temperatures to increases in long-term mean global hurricane intensity," delivering another major blow to the contentions of Emanuel (2005) and Webster *et al.* (2005) while stating that "the question of whether hurricane intensity is globally trending upwards in a warming climate will likely remain a point of debate in the foreseeable future."

As a result of the many investigations of the subject that have been conducted over the past several years, there currently appears to be no factual basis for claiming that planet-wide hurricane frequency and/or intensity will rise in response to potential future global warming. Nevertheless, parties pushing for restrictions on anthropogenic CO<sub>2</sub> emissions continue to do so, citing the claims of Emanuel (2005) and Webster *et al.* (2005) as major reasons for their unrelenting efforts, which necessitates our highlighting the findings of two additional papers.

Based on the demographic and economic findings of Pielke *et al.* (2000), Pielke *et al.* (2005) report that by the year 2050, "for every additional dollar in damage that the Intergovernmental Panel on Climate Change expects to result from the effects of global warming on tropical cyclones, we should expect between \$22 and \$60 of increase in damage due to population growth and wealth." This being the case, they merely state the obvious when they say that "the primary factors that govern the magnitude and patterns of future damages and causalities are how society develops and prepares for storms rather than any presently conceivable future changes in the frequency and intensity of the storms." Nevertheless, Pielke *et al.* note that many climate alarmists continue to claim a significant hurricane-global warming connection for the purpose of advocating massive anthropogenic CO<sub>2</sub> emissions reductions, which in their estimation "simply will not be effective with respect to addressing future hurricane impacts," additionally noting that "there are much, much better ways to deal with the threat of hurricanes than with energy policies (e.g., Pielke and Pielke, 1997)."

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/h/hurricaneglobal.php>.

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#### **5.4. ENSO**

Computer model simulations have given rise to three claims regarding the influence of global warming on ENSO events: (1) global warming will increase the *frequency* of ENSO events, (2) global warming will increase the *intensity* of ENSO events, and (3) weather-related disasters will be exacerbated under El Niño conditions. Here, we test the validity of these assertions, demonstrating they are in conflict with the observational record. We begin by highlighting studies that suggest the virtual world of ENSO, as simulated by state-of-the-art climate models, is also at variance with reality.

Additional information on this topic, including reviews on ENSO not discussed here, can be found at [http://www.co2science.org/subject/e/subject\\_e.php](http://www.co2science.org/subject/e/subject_e.php) under the heading ENSO.

##### **5.4.1. Model Inadequacies**

A major part of this distortion is due to the inability of climate models to correctly simulate tropical sea surface temperatures. In a comparison of 24 coupled ocean-atmosphere climate models, for example, Latif *et al.* (2001) report that "almost all models (even those employing flux corrections) still have problems in simulating the SST climatology." They also note that "only a few of the coupled models simulate the El Niño/Southern Oscillation (ENSO) in terms of gross equatorial SST anomalies realistically." And they state that "no model has been found that simulates realistically all aspects of the interannual SST variability." Hence, because "changes in sea surface temperature are both the cause and consequence of wind fluctuations," and because these phenomena figure prominently in the El Niño-La Niña oscillation, it is not surprising that Fedorov and Philander (2000) conclude that current climate models do not do a good job of determining the potential effects of global warming on ENSO.

Plain old human ignorance likely also plays a role in the models' failure to simulate ENSO. According to Overpeck and Webb (2000), there is evidence that "ENSO may change in ways that we do not yet understand," which "ways" have clearly not yet been modeled. White *et al.* (2001), for example, found that "global warming and cooling during earth's internal mode of

interannual climate variability [the ENSO cycle] arise from fluctuations in the global hydrological balance, not the global radiation balance," and that these fluctuations are the result of no known forcing of either anthropogenic or extraterrestrial origin, although Cerveny and Shaffer (2001) make a case for a *lunar* forcing of ENSO activity, which also is not included in any climate model.

Another example of the inability of today's most sophisticated climate models to properly describe El Niño events is provided by Landsea and Knaff (2000), who employed a simple statistical tool to evaluate the skill of twelve state-of-the-art climate models in real-time predictions of the development of the 1997-98 El Niño. They found that the models exhibited essentially no skill in forecasting this very strong event at lead times ranging from 0 to 8 months. They also determined that no models were able to anticipate even one-half of the actual amplitude of the El Niño's peak at a medium range lead-time of 6 to 11 months. Hence, they state that "since no models were able to provide useful predictions at the medium and long ranges, *there were no models that provided both useful and skillful forecasts for the entirety of the 1997-98 El Niño*" [authors' italics].

Given the inadequacies listed above, it is little wonder several scientists have criticized model simulations of current ENSO behavior, including Walsh and Pittcock (1998), who say "there is insufficient confidence in the predictions of current models regarding any changes in ENSO," and Fedorov and Philander (2000), who say that "at this time, it is impossible to decide which, if any, are correct." As a result, there is also little reason to believe that current climate models can correctly predict ENSO behavior under *future* conditions of *changed* climate.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/e/ensomo.php>.

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#### 5.4.2. Relationship to Extreme Weather

Changnon (1999) determined that adverse weather events attributed to the El Niño of 1997-98 negatively impacted the United States economy to the tune of 4.5 billion dollars and contributed to the loss of 189 lives, which is serious indeed. *On the other hand*, he determined that El Niño-related *benefits* amounted to approximately 19.5 billion dollars - resulting primarily from reduced energy costs, industry sales, and the lack of normal hurricane damage - and that a total of 850 lives were *saved* due to the reduced amount of bad winter weather. Thus, the net impact of the 1997-98 El Niño on the United States, according to Changnon, was "surprisingly positive," in stark contrast to what was often reported in the media and by climate alarmists, who tend, in his words, "to focus only on the negative outcomes."

Another of the "surprisingly positive" consequences of El Niños is their tendency to moderate Atlantic hurricane frequencies. Working with data from 1950 to 1998, Wilson (1999) determined that the probability of having three or more intense hurricanes during a warmer El Niño year was approximately 14%, while during a cooler non-El Niño year the probability jumped to 53%. Similarly, in a study of tropical storm and hurricane strikes along the southeast coast of the United States over the entire last century, Muller and Stone (2001) determined that "more tropical storm and hurricane events can be anticipated during La Niña seasons [3.3 per season] and fewer during El Niño seasons [1.7 per season]." And in yet another study of Atlantic basin hurricanes, this one over the period 1925 to 1997, Pielke and Landsea (1999) reported that average hurricane wind speeds during warmer El Niño years were about six meters per second *lower* than during cooler La Niña years. In addition, they reported that hurricane damage during cooler La Niña years was *twice as great* as during warmer El Niño years. These year-to-year variations thus indicate that, if anything, hurricane frequency and intensity - as well as damage - tend to *decrease* under warmer El Niño conditions, which is just the opposite of the impression that is typically conveyed to the public by climate alarmists.

Much the same story is filtering out of other parts of the world. In the North Indian Ocean, Singh *et al.* (2000) studied tropical cyclone data pertaining to the period 1877-1998, finding that tropical cyclone frequency there *declined* during the months of *most severe* cyclone formation - November and May - *when ENSO was in a warm phase*. In New Zealand, De Lange and Gibb (2000) studied storm surge events recorded by several tide gauges in Tauranga Harbor over the period 1960-1998, finding a considerable decline in both the annual number of such events *and*

*their magnitude* in the latter (warmer) half of the nearly four-decade-long record, additionally noting that La Niña seasons typically experienced more storm surge days than El Niño seasons. And in Australia, Kuhnel and Coates (2000) found that over the period 1876-1991, yearly fatality event-days due to floods, bushfires and heatwaves were actually greater in cooler La Niña years than in warmer El Niño years.

Apparently, even tiny-brained birds seem to know better than climate alarmists when it comes to the dangers of La Niña vs. El Niño. In a study of breeding populations of Cory's Shearwaters on the Tremiti Islands of Italy, for example, Brichetti *et al.* (2000) found that, contrary to even *their* hypothesis, survival rates during El Niño years were greater than during La Niña years, which they ultimately attributed to the soothing influence of La Niña on Atlantic hurricanes.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/e/ensoew.php>.

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### 5.4.3. Relationship to Global Warming

All of the claims regarding the influence of global warming on ENSO events are derived from climate model simulations. Timmermann *et al.* (1999), for example, developed a global climate model which, according to them, operates with sufficient resolution to address the issue of whether "human-induced 'greenhouse' warming affects, or will affect, ENSO." When running this model with increasing greenhouse-gas concentrations, more frequent El-Niño-like conditions do indeed occur. However, this is *not* what observational data reveal to be the case. The frequent and strong El Niño activity of the recent past is in actuality no different from that of a number of other such episodes of prior centuries, when it was considerably colder than it is today, as described in several of the papers highlighted below. And in many instances, the El Niño activity of the recent past is shown to be vastly *inferior* to that of colder times.

Evans *et al.* (2002) reconstructed gridded Pacific Ocean sea surface temperatures from coral stable isotope ( $\delta^{18}\text{O}$ ) data, from which they assessed ENSO activity over the period 1607-1990. The results of their analysis showed that a period of relatively vigorous ENSO activity over the colder-than-present period of 1820-1860 was "similar to [that] observed in the past two decades." Likewise, in a study that was partly based upon the instrumental temperature record for the period 1876-1996, Allan and D'Arrigo (1999) found four persistent El Niño sequences similar to that of the 1990s; and using tree-ring proxy data covering the period 1706 to 1977, they found several other ENSO events of prolonged duration. In fact, there were four or five persistent El Niño sequences in each of the 18th and 19th centuries, which were both significantly colder than the final two decades of the 20th century, leading them to conclude there is "no evidence for an enhanced greenhouse influence in the frequency or duration of 'persistent' ENSO event sequences."

In a somewhat different type of study, Brook *et al.* (1999) analyzed the layering of couplets of inclusion-rich calcite over inclusion-free calcite, and darker aragonite over clear aragonite, in two stalagmites from Anjohibe Cave in Madagascar, comparing their results with historical records of El Niño events and proxy records of El Niño events and sea surface temperatures derived from ice core and coral data. This exercise revealed that the cave-derived record of El Niño events compared well with the historical and proxy ice core and coral records; and these data indicated, in Brook *et al.*'s words, that "the period 1700-50 possibly witnessed the highest frequency of El Niño events in the last four and a half centuries while the period 1780-1930 was the longest period of consistently high El Niño occurrences," both of which periods were considerably cooler than the 1980s and 90s.

In another multi-century study, Meyerson *et al.* (2003) analyzed an annually-dated ice core from the South Pole that covered the period 1487-1992, specifically focusing on the marine biogenic sulfur species methanesulfonate (MS), after which they used orthogonal function analysis to calibrate the high-resolution MS series with associated environmental series for the period of overlap (1973-92). This procedure allowed them to derive a five-century history of ENSO activity and southeastern Pacific sea-ice extent, the latter of which parameters they say

"is indicative of regional temperatures within the Little Ice Age period in the southeastern Pacific sea-ice sector."

In analyzing these records, Meyerson *et al.* noted a shift at about 1800 towards generally cooler conditions. This shift was concurrent with an *increase* in the frequency of El Niño events in the ice core proxy record, which is contrary to what is generally predicted by climate models. On the other hand, their findings were harmonious with the historical El Niño chronologies of both South America (Quinn and Neal, 1992) and the Nile region (Quinn, 1992; Diaz and Pulwarty, 1994), which depict, in their words, "increased El Niño activity during the period of the Little Ice Age (nominally 1400-1900) and decreased El Niño activity during the Medieval Warm Period (nominally 950-1250)," as per Anderson (1992) and de Putter *et al.*, 1998).

Taking a little longer look back in time were Cobb *et al.* (2003), who generated multi-century monthly-resolved records of tropical Pacific climate variability over the last millennium by splicing together overlapping fossil-coral records from the central tropical Pacific, which exercise allowed them "to characterize the range of natural variability in the tropical Pacific climate system with unprecedented fidelity and detail." In doing so, they discovered that "ENSO activity in the seventeenth-century sequence [was] not only stronger, but more frequent than ENSO activity in the late twentieth century." They also found "there [were] 30-yr intervals during both the twelfth and fourteenth centuries when ENSO activity [was] greatly reduced relative to twentieth-century observations." Once again, therefore, we have a situation where ENSO activity was much greater and more intense during the cold of the Little Ice Age than the warmth of the late 20th century.

Inching still further back in time, Eltahir and Wang (1999) used water-level records of the Nile River as a proxy for El Niño episodes over the past 14 centuries. This approach indicated that although the frequency of El Niño events over the 1980s and 90s was high, it was not without precedent, being similar to values observed near the *start* of the 20th-century and much the same as those "experienced during the last three centuries of the first millennium," which latter period, according to Esper *et al.* (2002), was also significantly cooler than the latter part of the 20th century.

Woodroffe *et al.* (2003) found pretty much the same thing, but over an even longer period of time. Using oxygen isotope ratios obtained from *Porites* microatolls at Christmas Island in the central Pacific to provide high-resolution proxy records of ENSO variability since 3.8 thousand years ago (ka), they found, in their words, that "individual ENSO events in the late Holocene [3.8-2.8 ka] appear at least as intense as those experienced in the past two decades." In addition, they note that "geoarcheological evidence from South America (Sandweiss *et al.*, 1996), Ecuadorian varved lake sediments (Rodbell *et al.*, 1999), and corals from Papua New Guinea (Tudhope *et al.*, 2001) indicate that ENSO events were considerably weaker or absent between 8.8 and 5.8 ka," which was the warmest part of the Holocene. In fact, they report that "faunal remains from archeological sites in Peru (Sandweiss *et al.*, 2001) indicate that the onset of modern, rapid ENSO recurrence intervals was achieved only after ~4-3 ka," or during the long cold interlude that preceded the Roman Warm Period (McDermott *et al.*, 2001).

Also concentrating on the mid to late Holocene were McGregor and Gagan (2004), who used several annually-resolved fossil *Porites* coral  $\delta^{18}\text{O}$  records to investigate the characteristics of ENSO events over a period of time in which the earth cooled substantially. For comparison, study of a modern coral core provided evidence of ENSO events for the period 1950-1997, the results of which analysis suggest they occurred at a rate of 19 events/century. The mid-Holocene coral  $\delta^{18}\text{O}$  records, on the other hand, showed reduced rates of ENSO occurrence: 12 events/century for the period 7.6-7.1 ka, 8 events/century for the period 6.1-5.4 ka, and 6 events/century at 6.5 ka. For the period 2.5-1.7 ka, however, the results were quite different, with all of the coral records revealing, in the words of McGregor and Gagan, "large and protracted  $\delta^{18}\text{O}$  anomalies indicative of particularly severe El Niño events." They note specifically, for example, that "the 2.5 ka Madang PNG coral records a protracted 4-year El Niño, like the 1991-1994 event, but almost twice the amplitude of [the] 1997-1998 event (Tudhope *et al.*, 2001)." In addition, they say that "the 2 ka Muschu Island coral  $\delta^{18}\text{O}$  record shows a severe 7-year El Niño, longer than any recorded Holocene or modern event." And they add that "the 1.7 ka *Porites* microatoll of Woodroffe *et al.* (2003) also records an extreme El Niño that was twice the amplitude of the 1997-1998 event." Taken together, these several sets of results portray what McGregor and Gagan describe as a "mid-Holocene El Niño suppression and late Holocene amplification."

That there tend to be fewer and weaker ENSO events during warm periods has further been documented by Riedinger *et al.* (2002). In a 7,000-year study of ENSO activity in the vicinity of the Galapagos Islands, they determined that "mid-Holocene [7130 to 4600 yr BP] El Niño activity was infrequent," when, of course, global air temperature was significantly warmer than it is now, but that both the "frequency and intensity of events increased at about 3100 yr BP," when it finally cooled below current temperatures. More specifically, throughout the former 2530-year warm period, their data revealed the existence of 23 strong to very strong El Niños and 56 moderate events; while throughout the most recent (and significantly colder) 3100-year period, they identified 80 strong to very strong El Niños and 186 moderate events. These numbers correspond to rates of 0.9 strong and 2.2 moderate occurrences per century in the earlier warm period and 2.7 strong and 6.0 moderate occurrences per century in the latter cool period, suggestive of an approximate tripling of the rate of occurrence of both strong and moderate El Niños in going from the warmth of the Holocene "Climatic Optimum" to the colder conditions of the past three millennia.

Similar results have been reported by Andrus *et al.* (2002) and Moy *et al.* (2002). According to Andrus *et al.*, sea surface temperatures off the coast of Peru some 6000 years ago were 3 to 4°C warmer than what they were over the decade of the 1990s and provided little evidence of any El Niño activity. Nearby, Moy *et al.* analyzed a sediment core from lake Laguna Pallcacocha in the southern Ecuadorian Andes, producing a proxy measure of ENSO over the past 12,000 years. For the moderate and strong ENSO events detected by their analytical techniques (weaker events are not registered), these researchers state that "the overall trend exhibited in the Pallcacocha record includes a low concentration of events in the early Holocene, followed

by increasing occurrence after 7,000 cal. yr BP, with peak event frequency occurring at ~1,200 cal. yr BP," after which the frequency of events declines dramatically to the present.

With respect to the last 1,200 years of this record, however, the decline in the frequency of ENSO events is anything but smooth. In coming out of the Dark Ages Cold Period, which was one of the coldest intervals of the Holocene (McDermott *et al.*, 2001), the number of ENSO events experienced by the earth drops by an order of magnitude, from a high of approximately 33 events per 100 yr to a low of about 3 events per 100 yr, centered approximately on the year AD 1000, which is right in the middle of the Medieval Warm Period, as delineated by the work of Esper *et al.* (2002). Then, at approximately AD 1250, the frequency of ENSO events exhibits a new peak of approximately 27 events per 100 yr in the midst of the longest sustained cold period of the Little Ice Age, again as delineated by the work of Esper *et al.* Finally, ENSO event frequency declines in zigzag fashion to a low on the order of 4 to 5 events per 100 yr at the start of the Modern Warm Period, which according to the temperature history of Esper *et al.* begins at about 1940.

Going even further back in time, in a study of a recently revised New England varve chronology derived from proglacial lakes formed during the recession of the Laurentide ice sheet some 17,500 to 13,500 years ago, Rittenour *et al.* (2000) determined that "the chronology shows a distinct interannual band of enhanced variability suggestive of El Niño-Southern Oscillation (ENSO) teleconnections into North America during the late Pleistocene, when the Laurentide ice sheet was near its maximum extent ... during near-peak glacial conditions." But during the *middle* of the Holocene, when it was *considerably* warmer, even than it is today, Overpeck and Webb (2000) report that data from corals suggest that "interannual ENSO variability, as we now know it, was substantially reduced, or perhaps even absent."

In summing up the available evidence pertaining to the effect of temperature on the frequency of occurrence and strength of ENSO events, we have one of the most sophisticated climate models ever developed to deal with the ENSO phenomenon implying that global warming will promote more frequent El Niño-like conditions; while we have a number of real-world observations demonstrating that El Niño-like conditions during the latter part of the 20th century (claimed by climate alarmists to be the warmest period of the past two thousand years) are not unprecedented in terms of their frequency or magnitude and are, in fact, not much different from those that occurred during much colder times. In addition, we have a number of long-term records that suggest that when the earth was significantly warmer than it is currently, ENSO events were *substantially reduced* or perhaps even *absent!*

Clearly, the models -- and their blind-to-everything-else followers -- have a problem. They are one hundred and eighty degrees out of phase with reality.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/e/ensogw.php>.

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### **5.5. Precipitation Variability**

Climate alarmists often contend that global warming is responsible for creating more frequent and greater extremes of various types of weather. We here investigate this claim as it pertains to precipitation, focusing on the occurrence of droughts and floods as described in several papers we have reviewed on our website for Africa, Asia and North America.

Additional information on this topic, including reviews on precipitation not discussed here, can be found at [http://www.co2science.org/subject/p/subject\\_p.php](http://www.co2science.org/subject/p/subject_p.php) under the heading Precipitation.

#### **5.5.1. Africa**

Nicholson and Yin (2001) described climatic and hydrologic conditions in equatorial East Africa from the late 1700s to close to the present, based on histories of the levels of ten major African lakes. They also used a water balance model to infer changes in rainfall associated with the different conditions, concentrating most heavily on Lake Victoria. This work revealed "two starkly contrasting climatic episodes." The first, which began sometime prior to 1800 and was characteristic of Little Ice Age conditions, was one of "drought and desiccation throughout Africa." This arid episode, which was most extreme during the 1820s and 30s, was accompanied by extremely low lake levels. As the two researchers describe it, "Lake Naivash was reduced to a puddle ... Lake Chad was desiccated ... Lake Malawi was so low that local inhabitants traversed dry land where a deep lake now resides ... Lake Rukwa [was] completely desiccated ... Lake Chilwa, at its southern end, was very low and nearby Lake Chiuta almost dried up." Throughout this unfortunate period, they report that "intense droughts were ubiquitous." Some, in fact, were "long and severe enough to force the migration of peoples and create warfare among various tribes."

As the Little Ice Age's grip on the world began to loosen in the mid to latter part of the 1800s, however, things began to tend towards the better for most of the continent. Nicholson and Yin report that "semi-arid regions of Mauritania and Mali experienced agricultural prosperity and abundant harvests ... the Niger and Senegal Rivers were continually high; and wheat was grown in and exported from the Niger Bend region." Across the length of the northern Sahel, in fact, maps and geographical reports described the presence of "forests." As the nineteenth century came to an end and the twentieth century began, however, there was a slight lowering of lake levels, but nothing like what had occurred a century earlier (i.e., variability was much reduced). And then, in the latter half of the twentieth century, things once again began to pick up for the Africans, with the levels of some of the lakes actually rivaling the high-stands characteristic of the years of transition to the Modern Warm Period.

Concentrating on the more recent past, Nicholson (2001) says the most significant climatic change has been "a long-term reduction in rainfall in the semi-arid regions of West Africa," which has been "on the order of 20 to 40% in parts of the Sahel." There have been, she says, "three decades of protracted aridity," and "nearly all of Africa has been affected ... particularly since the 1980s." *However*, she goes on to note that "the rainfall conditions over Africa during the last 2 to 3 decades are not unprecedented," and that "a similar dry episode prevailed during most of the first half of the 19th century."

Describing the situation in more detail, Nicholson says "the 3 decades of dry conditions evidenced in the Sahel are not in themselves evidence of irreversible global change." And especially, we would add, are they not evidence of *global warming-induced* change. Why not? Because a longer historical perspective of the type we are constantly striving to obtain clearly indicates, as noted by Nicholson, that an even *longer* period of *similar* dry conditions occurred between 1800 and 1850. In addition, this remarkable dry period occurred when the earth was still in the clutches of the Little Ice Age, a period of cold that is without precedent in at least the last 6500 years ... *even in Africa* (Lee-Thorp *et al.*, 2001). Hence, there is no reason to think that the most recent two- to three-decade Sahelian drought was in any way unusual or that it was caused by the higher temperatures of that period.

Also taking a longer view of the subject were Nguetsop *et al.* (2004), who developed a high-resolution proxy record of West African precipitation based on analyses of diatoms recovered from a sediment core retrieved from Lake Ossa, West Cameroon, which they describe as "the first paleohydrological record for the last 5500 years in the equatorial near-coastal area, east of the Guinean Gulf." They reported that this record provides evidence for alternating periods of increasing and decreasing precipitation "at a millennial time scale for the last 5500 years," which oscillatory behavior they interpret as being "a result of south/northward shifts of the Intertropical Convergence Zone," specifically noting that "a southward shift of the ITCZ, combined with strengthened northern trade winds, was marked by low and high precipitation at the northern subtropics and the subequatorial zone, respectively," and that "these events occurred in coincidence with cold spells in the northern Atlantic." As with so many other temperature and precipitation records from around the world, their data for West Africa add to the growing body of evidence for the existence of a millennial-scale oscillation of climate that alternately brings either warmer or cooler temperatures or wetter or drier conditions to each of the locations it influences as it reverberates down through the ages.

Most recently, Therrell *et al.* (2006) developed "the first tree-ring reconstruction of rainfall in tropical Africa using a 200-year regional chronology based on samples of *Pterocarpus angolensis* [a deciduous tropical hardwood known locally as Mukwa] from Zimbabwe." This record revealed that "a decadal-scale drought reconstructed from 1882 to 1896 matches the most severe sustained drought during the instrumental period (1989-1995)," and that "an even more severe drought is indicated from 1859 to 1868 in both the tree-ring and documentary data." They report, for example, that the year 1860, which exhibited the lowest reconstructed rainfall value during this period, was described in a contemporary account from Botswana (where part of their tree-ring chronology originated) as "a season of 'severe and universal



drought' with 'food of every description' being 'exceedingly scarce' and the losses of cattle being 'very severe' (Nash and Endfield, 2002)." At the other end of the moisture spectrum, they report that "a 6-year wet period at the turn of the nineteenth century (1897-1902) exceeds any wet episode during the instrumental era."

Consequently, for a large part of central southern Africa, as well as the other parts of the continent described above, it is clear that the supposedly unprecedented global warming of the 20th century has *not* resulted in an intensification of extreme dry and wet periods. If anything, just the *opposite* appears to have occurred.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/p/variabilafrica.php>.

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## 5.5.2. Asia

Pederson *et al.* (2001) developed tree-ring chronologies for northeastern Mongolia and used them to reconstruct annual precipitation and streamflow histories for the period 1651-1995. Working with both standard deviations and 5-year intervals of extreme wet and dry periods, they found that "variations over the recent period of instrumental data are not unusual relative to the prior record." They note, however, that their reconstructions "appear to show more frequent extended wet periods in more recent decades," but they say that this observation "does not demonstrate unequivocal evidence of an increase in precipitation as suggested by

some climate models." Spectral analysis of the data also revealed significant periodicities around 12 and 20-24 years, which they suggested may constitute "possible evidence for solar influences in these reconstructions for northeastern Mongolia."

Kripalani and Kulkarni (2001) studied seasonal summer monsoon (June-September) rainfall data from 120 east Asia stations for the period 1881-1998. A series of statistical tests they applied to these data revealed the presence of short-term variability in rainfall amounts on decadal and longer time scales, the longer "epochs" of which were found to last for about three decades over China and India and for approximately five decades over Japan. With respect to long-term trends, however, none were detected. Consequently, the history of summer rainfall trends in east Asia does *not* support climate-alarmist claims of intensified monsoonal conditions in this region as a result of CO<sub>2</sub>-induced global warming. As for the decadal variability inherent in the record, the two researchers say it "appears to be just a part of natural climate variations."

Taking a much longer look at the Asian monsoon were Ji *et al.* (2005), who used reflectance spectroscopy on a sediment core taken from a lake in the northeastern part of the Qinghai-Tibetan Plateau to obtain a continuous high-resolution proxy record of the Asian monsoon over the past 18,000 years. This project indicated that monsoonal moisture since the late glacial period had been subject to "continual and cyclic variations," among which was a "very abrupt onset and termination" of a 2,000-year dry spell that started about 4200 years ago (yr BP) and ended around 2300 yr BP. Other variations included the well-known centennial-scale cold and dry spells of the Dark Ages Cold Period (DACP) and Little Ice Age (LIA), which lasted from 2100 yr BP to 1800 yr BP and 780 yr BP to 400 yr BP, respectively, while sandwiched between them was the warmer and wetter Medieval Warm Period, and preceding the DACP was the Roman Warm Period. Time series analyses of the sediment record also revealed several statistically significant periodicities (123, 163, 200 and 293 years, all above the 95% level), with the 200-year cycle matching the de Vries or Suess *solar* cycle, implying that changes in solar activity are important triggers for some of the recurring precipitation changes in that part of Asia. Hence, it is clear that large and abrupt fluctuations in the Asian monsoon have occurred numerous times and with great regularity throughout the Holocene, and that the sun played an important role in orchestrating them.

Also working on the Tibetan Plateau were Shao *et al.* (2005), who used seven Qilian juniper ring-width chronologies from the northeastern part of the Qaidam Basin to reconstruct a thousand-year history of annual precipitation there. In doing so, they discovered that annual precipitation had fluctuated at various intervals and to various degrees throughout the entire past millennium. Wetter periods occurred between 1520 and 1633, as well as between 1933 and 2001, although precipitation has declined somewhat since the 1990s. Drier periods, on the other hand, occurred between 1429 and 1519 and between 1634 and 1741. With respect to variability, the scientists report that the magnitude of variation in annual precipitation was about 15 mm before 1430, increased to 30 mm between 1430 and 1850, and declined thereafter to the present. These several findings suggest that either (1) there is nothing unusual about the planet's current degree of warmth, i.e., it is not unprecedented relative to that of the early part of the past millennium, or (2) unprecedented warming need not lead to

unprecedented precipitation or unprecedented precipitation variability ... *or both of the above*. We must conclude, therefore, that the findings of this study provide absolutely no support for the climate-alarmist contention that global warming leads to greater and more frequent precipitation extremes.

Based on analyses of tree-ring width data and their connection to large-scale atmospheric circulation, Touchan *et al.* (2005) developed summer (May-August) precipitation reconstructions for several parts of the eastern Mediterranean region (Turkey, Syria, Lebanon, Cyprus and Greece) that extend back in time anywhere from 115 to 600 years. Over the latter length of time, they found that May-August precipitation varied on multiannual and decadal timescales, but that on the whole there were no long-term trends. The longest dry period occurred in the late 16th century (1591-1595), while there were two extreme wet periods: 1601-1605 and 1751-1755. In addition, both extremely strong and weak precipitation events were found to be more variable over the intervals 1520-1590, 1650-1670 and 1850-1930. Consequently, the results of this study also demonstrate there was nothing unusual or unprecedented about late 20th-century precipitation events in the eastern Mediterranean part of Asia that would suggest a CO<sub>2</sub> influence. If anything, as this region transited from the record cold of the Little Ice Age to the peak warmth of the Current Warm Period, May-August precipitation actually become *less* variable, in contrast to the climate-alarmist claim that extreme weather phenomena become more variable in the face of rising temperatures.

Last of all, Davi *et al.* (2006) used absolutely dated tree-ring-width chronologies obtained from five sampling sites in west-central Mongolia to derive individual precipitation models, the longest of which stretches from 1340 to 2002, additionally developing a reconstruction of streamflow that extends from 1637 to 1997. In the process of doing so, they discovered there was "much wider variation in the long-term tree-ring record than in the limited record of measured precipitation," which for the region they studied covers the period from 1937 to 2003. In addition, they say their streamflow history indicates that "the wettest 5-year period was 1764-68 and the driest period was 1854-58," while "the most extended wet period [was] 1794-1802 and ... extended dry period [was] 1778-83." For this part of Mongolia, therefore, which the researchers say is "representative of the central Asian region," there is no support to be found for the climate-alarmist contention that the "unprecedented warming" of the 20th century has led to increased variability in precipitation and streamflow. In fact, any tendencies that may be present in the data suggest just the *opposite*, which is pretty much the same story told by the other studies we describe in this section.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/p/variabilasia.php>.

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### 5.5.3. North America

Cronin *et al.* (2000) studied salinity gradients across sediment cores extracted from Chesapeake Bay, the largest estuary in the United States, in an effort to determine precipitation variability in the surrounding watershed over the prior millennium. Their efforts were successful; and they discovered there was a high degree of decadal and multidecadal variability in moisture conditions over the 1000-year period, with regional precipitation totals fluctuating by between 25 to 30%, often in extremely rapid shifts occurring over about a decade. They also determined that precipitation was generally greater over the last two centuries than it was over the eight previous centuries, with the exception of a portion of the Medieval Warm Period (AD 1250-1350), when the climate was extremely wet. In addition, they found that the region surrounding Chesapeake Bay had experienced several "mega-droughts" lasting from 60-70 years in length, some of which the researchers say "were more severe than twentieth century droughts." Likewise, across the continent, Haston and Michaelson (1997) developed a 400-year history of precipitation for 29 stations in coastal and near-interior California between San Francisco Bay and the U.S.-Mexican border using tree-ring chronologies; and their work also revealed that "region-wide precipitation during the last 100 years has been unusually high and less variable compared to other periods in the past."

Crossing the continent yet again, and dropping down to the Caribbean Sea, Watanabe *et al.* (2001) analyzed delta  $^{18}\text{O}/^{16}\text{O}$  and Mg/Ca ratios in cores obtained from a coral in an effort designed to examine seasonal variability in sea surface temperature and salinity there during the Little Ice Age. In doing so, they found that sea surface temperatures during this period were about 2°C colder than they are currently; while sea surface salinity exhibited greater variability

than it does now, indicating that during the Little Ice Age "wet and dry seasons were more pronounced."

Up in Canada, Zhang *et al.* (2001) analyzed the spatial and temporal characteristics of extreme precipitation events for the period 1900-1998, using what they describe as "the most homogeneous long-term dataset currently available for Canadian daily precipitation." This exercise indicated that decadal-scale variability was a dominant feature of both the frequency and intensity of extreme precipitation events; but it provided "no evidence of any significant long-term changes" in these indices during the 20th century. However, their analysis of precipitation *totals* (extreme and non-extreme) *did* reveal a slightly increasing trend across Canada during the period of study, but it was found to be due to increases in the number of *non-heavy* precipitation events. Consequently, the researchers concluded that "increases in the concentration of atmospheric greenhouse gases during the twentieth century have not been associated with a generalized increase in extreme precipitation over Canada."

Dropping down into the Uinta Basin Watershed of northeastern Utah, Gray *et al.* (2004) used cores extracted from 107 piñon pines at four different sites to develop a proxy record of annual (June to June) precipitation spanning the period AD 1226-2001. Based on their findings, they report that "single-year dry events before the instrumental period tended to be more severe than those after 1900," and that decadal-scale dry events were longer and more severe prior to 1900 as well. In particular, they found that "dry events in the late 13th, 16th, and 18th centuries surpass the magnitude and duration of droughts seen in the Uinta Basin after 1900." At the other end of the spectrum, they report that the 20th century contained two of the strongest wet intervals (1938-1952 and 1965-1987), although the two periods were only the *seventh* and *second* most intense wet regimes, respectively, of the entire record. Hence, it would appear that in conjunction with 20th-century global warming, precipitation extremes (both high and low) within the Uinta Basin of northeastern Utah have become *attenuated* as opposed to *amplified*.

Last of all, we come to the study of Rasmussen *et al.* (2006), who had previously demonstrated that "speleothems from the Guadalupe Mountains in southeastern New Mexico are annually banded, and variations in band thickness and mineralogy can be used as a record of regional relative moisture (Asmerom and Polyak, 2004)." In their new study, therefore, they continued this tack, concentrating on "two columnar stalagmites collected from Carlsbad Cavern (BC2) and Hidden Cave (HC1) in the Guadalupe Mountains." So what did they find?

The three researchers report that "both records, BC2 and HC1, suggest periods of dramatic precipitation variability over the last 3000 years, exhibiting large shifts *unlike anything seen in the modern record* [our italics]." Second, they report that the time interval from AD 900-1300 coincides with the well-known Medieval Warm Period and "shows dampened precipitation variability and overall drier conditions" that are "consistent with the idea of more frequent La Niña events and/or negative PDO phases causing elevated aridity in the region during this time." Third, they indicate that the preceding and following colder centuries "show increased precipitation variability ... coinciding with increased El Niño flooding events."

In light of these observations, it is clear that climate alarmists go way overboard when they characterize significant droughts and floods of recent times as "unprecedented" over the past millennium or more, as well as when they attribute them to CO<sub>2</sub>-induced global warming. Moisture extremes much greater than those observed in the modern era are neither unusual nor manmade; they are simply a normal part of earth's natural climatic variability. Also contradicting climate-alarmist dogma, the three researchers' work, like that of many others, suggests that dramatic El Niño events are typically *less* significant during multi-century warm periods than they are during multi-century cold periods.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/p/variabilnortham.php>.

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### **5.6. Storms**

Among the highly publicized changes in weather phenomena that are predicted to attend the ongoing rise in the air's CO<sub>2</sub> content are increases in the frequency and severity of all types of

storms. As a result, and in an effort to determine if these predictions have any validity, many researchers have examined historical and proxy records in an attempt to determine how temperature changes over the past millennium or two have impacted this aspect of earth's climate. This section reviews what some of them have learned about storm trends, focusing on Europe and North America.

A number of studies have reported increases in North Atlantic storminess over the last two decades of the 20th century (Jones *et al.*, 1997; Gunther *et al.*, 1998; Dickson *et al.*, 2000). Since climate alarmists claim this period was one of the warmest - if not *the* warmest - of the past couple of millennia, this observation might appear to vindicate their view of the subject. When much longer time periods are considered, however, just the *opposite* is typically found to be the case.

In reviewing some of these more *comprehensive* analyses, we begin with the study of Dawson *et al.* (2002), who searched daily meteorological records from Stornoway (Outer Hebrides), Lerwick (Shetland Islands), Wick (Caithness) and Fair Isle (west of the Shetland Islands) for all data pertaining to gale-force winds over the period 1876-1996, which they used to construct a history of storminess for that period for northern and northwestern Scotland. This history indicated that although North Atlantic storminess and associated wave heights had indeed increased over the prior two decades, storminess in the North Atlantic region "was considerably more severe during parts of the nineteenth century than in recent decades." In addition, whereas the modern increase in storminess appeared to be associated with a spate of substantial positive values of the North Atlantic Oscillation (NAO) index, they say that "this was not the case during the period of exceptional storminess at the close of the nineteenth century." During that earlier period, the conditions that fostered modern storminess were apparently overpowered by something even more potent, i.e., *cold temperatures*, which in the view of Dawson *et al.* led to an expansion of sea ice in the Greenland Sea that expanded and intensified the Greenland anticyclone, which in turn led to the North Atlantic cyclone track being displaced farther south. Additional support for this view is provided by the hypothesis propounded by Clarke *et al.* (2002), who postulated that a southward spread of sea ice and polar water results in an increased thermal gradient between 50°N and 65°N that intensifies storm activity in the North Atlantic and supports dune formation in the Aquitaine region of southwest France.

The results of these two studies suggest that the increased storminess and wave heights observed in the European sector of the North Atlantic Ocean over the past two decades are not the result of global warming. Rather, they are associated with the most recent periodic increase in the NAO index. Furthermore, a longer historical perspective reveals that North Atlantic storminess was even more severe than it is now during the latter part of the nineteenth century, when it was significantly colder than it is now. In fact, the storminess of that much colder period was so great that it was actually decoupled from the NAO index. Hence, the long view of history suggests that the global warming of the past century or so has actually led to an overall *decrease* in North Atlantic storminess.

Additional evidence for the recent century-long decrease in storminess in and around Europe comes from the study of Bijl *et al.* (1999), who analyzed long-term sea level records from several coastal stations in northwest Europe. According to these researchers, "although results show considerable natural variability on relatively short (decadal) time scales," there is "no sign of a significant increase in storminess ... over the complete time period of the data sets." In the southern portion of the North Sea, however, where natural variability was more moderate, they *did* find a trend, but it was "a tendency towards a *weakening* [our italics] of the storm activity over the past 100 years."

Much the same results were obtained by Pirazzoli (2000), who analyzed tide-gauge, wind and atmospheric pressure data over the period 1951-1997 for the northern portion of the Atlantic coast of France. In that study, the number of atmospheric depressions (storms) and strong surge winds were found to be decreasing in frequency. In addition, it was reported that "ongoing trends of climate variability show a decrease in the frequency and hence the gravity of coastal flooding."

Tide-gauge data have also been utilized as proxies for storm activity in England. Based on high-water measurements made at the Liverpool waterfront over the period 1768-1999, Woodworth and Blackman (2002) found that the annual maximum surge-at-high-water declined at a rate of  $0.11 \pm 0.04$  meters per century, suggesting that the winds responsible for producing high storm surges were much stronger and/or more common during the early part of the record (colder Little Ice Age) than the latter part (Modern Warm Period).

On a somewhat different front, and quite a ways inland, Bielec (2001) analyzed thunderstorm data from Cracow, Poland for the period 1896-1995, finding an average of 25 days of such activity per year, with a non-significant linear-regression-derived increase of 1.6 storm days from the beginning to the end of the record. From 1930 onward, however, the trend was *negative*, revealing a similarly-derived decrease of 1.1 storm days. In addition, there was a *decrease* in the annual number of thunderstorms with hail over the entire period and a decrease in the frequency of storms producing precipitation in excess of 20 mm.

In introducing a study they conducted in Switzerland, Stoffel *et al.* (2005) noted that *debris flows* are a type of mass movement that frequently causes major destruction in alpine areas; and they reported that since 1987 there had been an apparent above-average occurrence of such events in the Valais region of the Swiss Alps, which had prompted some researchers to suggest that the increase was the result of global warming (Rebetez *et al.*, 1997). Consequently, Stoffel *et al.* used dendrochronological methods to determine if the recent increase in debris-flow events was indeed unusual, and if it appeared that it was, to see if it made sense to attribute it to CO<sub>2</sub>-induced global warming.

In extending the history of debris-flow events (1922-2002) back to the year 1605, they found that "phases with accentuated activity and shorter recurrence intervals than today existed in the past, namely after 1827 and until the late nineteenth century." What is more, the nineteenth century period of high-frequency debris flow was shown to coincide with a period of



higher flood activity in major Swiss rivers, while less frequent debris flow activity after 1922 corresponded with lower flooding frequencies. In addition, debris flows from extremely large mass movement events, similar to what occurred in 1993, were found to have "repeatedly occurred" in the historical past, and to have been of such substantial magnitude that, in the opinion of Stoffel *et al.*, the "importance of the 1993 debris-flow surges has to be thoroughly revised."

The results of Stoffel *et al.*'s study demonstrate that the apparent above-average number of debris flow events since 1987 was just that - *apparent*. In fact, they report that debris flows occurred "ever more frequently in the nineteenth century than they do today." As a result, they concluded that "correlations between global warming and modifications in the number or the size of debris-flow events, as hypothesized by, e.g., Haeberli and Beniston (1998), cannot, so far, be confirmed in the study area."

These findings clearly demonstrate the importance of evaluating the uniqueness of earth's contemporary climatic state - or the uniqueness of recent trends in various climate-related phenomena - over a much longer time span than just the past century or, even worse, merely a portion of it; for only when a multi-centennial or millennial view of the subject is available can one adequately evaluate the uniqueness of a climate-related phenomenon's recent behavior, let alone link that behavior to late 20th-century or early 21st-century global warming.

Noting that "a great amount of evidence for changing storminess over northwestern Europe is based on indirect data and reanalysis data rather than on station wind data," Smits *et al.* (2005) investigated trends in storminess over the Netherlands based on hourly records of 10-m wind speed observations made at thirteen meteorological stations scattered across the country that have uninterrupted records for the time period 1962-2002. This effort led to their discovery that "results for moderate wind events (that occur on average 10 times per year) and strong wind events (that occur on average twice a year) indicate a decrease in storminess over the Netherlands [of] between 5 and 10% per decade."

Moving cross-continent to the south and west, Raicich (2003) analyzed 62 years of sea-level data for the period 1 July 1939 to 30 June 2001 at Trieste, in the Northern Adriatic, to determine historical trends of surges and anomalies. This work revealed that weak and moderate positive surges did not exhibit any definite trends, while *strong* positive surges clearly became *less* frequent, *even in the face of a gradually rising sea level*, "presumably," in the words of Raicich, "as a consequence of a general weakening of the atmospheric activity," which was also found to have been the case for Brittany by Pirazzoli (2000).

Further north, Bjorck and Clemmensen (2004) extracted cores of peat from two raised bogs in the near-coastal part of southwest Sweden, from which they derived histories of wind-transported clastic material via systematic counts of quartz grains of various size classes that enabled them to calculate temporal variations in Aeolian Sand Influx (ASI), which has been shown to be correlated with winter wind climate in that part of the world. In doing so, they found that "the ASI records of the last 2500 years (both sites) indicate two timescales of winter

storminess variation in southern Scandinavia." Specifically, they note that "decadal-scale variation (individual peaks) seems to coincide with short-term variation in sea-ice cover in the North Atlantic and is thus related to variations in the position of the North Atlantic winter season storm tracks," while "centennial-scale changes - peak families, like high peaks 1, 2 and 3 during the Little Ice Age, and low peaks 4 and 5 during the Medieval Warm Period - seem to record longer-scale climatic variation in the frequency and severity of cold and stormy winters."

Bjorck and Clemmensen also found a striking association between the strongest of these winter storminess peaks and periods of reduced solar activity. They specifically note, for example, that the solar minimum between AD 1880 and 1900 "is almost exactly coeval with the period of increased storminess at the end of the nineteenth century, and the Dalton Minimum between AD 1800 and 1820 is almost coeval with the period of peak storminess reported here." In addition, they say that an event of increased storminess they dated to AD 1650 "falls at the beginning of the Maunder solar minimum (AD 1645-1715)," while further back in time they report high ASI values between AD 1450 and 1550 with "a very distinct peak at AD 1475," noting that this period coincides with the Sporer Minimum of AD 1420-1530. In addition, they call attention to the fact that the latter three peaks in winter storminess all occurred during the Little Ice Age and "are among the most prominent in the complete record."

Last of all, the two researchers report that *degree of humification* (DOH) intervals "correlate well with the classic late-Holocene climatic intervals," which they specifically state to include the Modern Climate Optimum (100-0 cal. yr BP), the Little Ice Age (600-100 cal. yr BP), the Medieval Warm Period (1250-600 cal. yr BP), the Dark Ages Cold Period (1550-1250 cal. yr BP) and the Roman Climate Optimum (2250-1550 cal. yr BP). There would thus appear to be little doubt that winter storms throughout southern Scandinavia were more frequent and intense during the multi-century Dark Ages Cold Period and Little Ice Age than they were during the Roman Warm Period, the Medieval Warm Period and the Modern Warm Period, providing strong evidence to refute the climate-alarmist contention that storminess tends to increase during periods of greater warmth. In the *real* world, just the *opposite* would appear to be the case.

Also working in Sweden were Barring and von Storch (2004), who - speaking of windstorms - say that *with the perspective of anthropogenic climate change*, the occurrence of such extreme events may "create the perception that ... the storms lately have become more violent, a trend that may continue into the future." Therefore, with the intent to test this inference, and relying on *data*, rather than *perception* to address the topic, these two researchers analyzed long time series of pressure readings for Lund (since 1780) and Stockholm (since 1823), analyzing (1) the annual number of pressure observations below 980 hPa, (2) the annual number of absolute pressure tendencies exceeding 16 hPa/12h, and (3) intra-annual 95th and 99th percentiles of the absolute pressure differences between two consecutive observations. Via these means they determined that the storminess time series they developed "are remarkably stationary in their mean, with little variations on time scales of more than one or two decades." In this regard, for example, they note that "the 1860s-70s was a period when the storminess indices showed

general higher values," as was the 1980s-90s, but that, subsequently, "the indices have returned to close to their long-term mean."

Barring and von Storch thus concluded their paper by stating that their storminess proxies "show no indication of a long-term robust change towards a more vigorous storm climate." In fact, during "the entire historical period," in their words, storminess was "remarkably stable, with no systematic change and little transient variability." Hence, we can conclude that for much of Sweden, at least, there was no warming-induced increase in windstorms over the entire transitional period between the Little Ice Age and the Modern Warm Period, which suggests there is little reason to believe that this *non*-trend would change with any further warming of the globe, in stark contradiction of what most climate alarmists continually claim will occur.

Returning to where we began our review of European storminess, and to some of the same researchers, we encounter the study of Dawson *et al.* (2004b), who examined the sedimentary characteristics of a series of Late Holocene coastal windstorm deposits found on the Scottish Outer Hebrides, an island chain that extends across the latitudinal range 56-58°N. These deposits form part of the landward edges of coastal sand accumulations that are intercalated with peat, the radiocarbon dating of which was used to construct a local chronology of the windstorms. This work revealed that "the majority of the sand units were produced during episodes of climate deterioration both prior to and after the well-known period of Medieval warmth." The researchers also say "the episodes of sand blow indicated by the deposits may reflect periods of increased cyclogenesis in the Atlantic associated with increased sea ice cover and an increase in the thermal gradient across the North Atlantic region." In addition, they report that "dated inferred sand drift episodes across Europe show synchronicity with increased sand mobilization in SW France, NE England, SW Ireland and the Outer Hebrides, implying a regional response to storminess with increased sand invasion during the cool periods of the Little Ice Age," citing the corroborative studies of Lamb (1995), Wintle *et al.* (1998), Gilbertson *et al.* (1999) and Wilson *et al.* (2001). Throughout a vast portion of the North Atlantic Ocean and adjacent Europe, therefore, storminess and wind strength appear to actually have been *inversely* related to mean global air temperature over most of the past two millennia, with the most frequent and intense events occurring both prior to and following the Medieval Warm Period. Consequently, the climate-alarmist claim that Europe will experience more intense and frequent windstorms if air temperatures continue to rise fails to resonate with reality.

Next, we come to the study of Dawson *et al.* (2004a), who examined 120- to 225-year records of gale-days per year from five locations scattered across Scotland, northwest Ireland and Iceland, which they compared with a much longer 2000-year record for the same general region. In doing so, they found that four of the five century-scale records showed a greater frequency of storminess in the cooler 1800s and early 1900s than throughout the remainder of the warmer 20th century. In addition, they report that "considered over the last ca. 2000 years, it would appear that winter storminess and climate-driven coastal erosion was at a minimum during the Medieval Warm Period," which again is just the *opposite* of what climate alarmists typically predict, i.e., more storminess with warmer temperatures.

Moving over to the United States, Zhang *et al.* (2000) used ten long-term records of storm surges derived from hourly tide gauge measurements to calculate annual values of the number, duration and integrated intensity of storms in eastern North America. Their analysis did not reveal any trends in storm activity during the twentieth century, which they say is suggestive of "a lack of response of storminess to minor global warming along the U.S. Atlantic coast during the last 100 yr."

Similar results were found by Boose *et al.* (2001). After scouring historical records to reconstruct hurricane damage regimes for an area composed of the six New England states plus adjoining New York City and Long Island for the period 1620-1997, they could discern "no clear century-scale trend in the number of major hurricanes." For the most recent and reliable 200-year portion of the record, however, the cooler 19th century had five of the highest-damage F3 category storms, while the warmer 20th century had only one such storm. Hence, as the earth experienced the warming associated with its recovery from the cold temperatures of the Little Ice Age, it would appear that this part of the planet (New England, USA) experienced, if anything, a *decline* in the intensity of severe hurricanes.

Going back even further in time, Noren *et al.* (2002) extracted sediment cores from thirteen small lakes distributed across a 20,000-km<sup>2</sup> region of Vermont and eastern New York, finding that "the frequency of storm-related floods in the northeastern United States has varied in regular cycles during the past 13,000 years (13 kyr), with a characteristic period of about 3 kyr." In addition, the most recent upswing in storminess did not begin with what climate alarmists call the *unprecedented warming* of the 20th century, but "at about 600 yr BP [Before Present], coincident with the beginning of the Little Ice Age." In reality, according to the authors, the increase in storminess was likely a product of natural changes in the Arctic Oscillation.

Moving to southern North America, land-falling hurricanes whose eyes crossed the coast between Cape Sable, Florida and Brownsville, Texas between 1896 and 1995 were the subject of investigation by Bove *et al.* (1998). With respect to those storms, the authors note that the first half of the 20th Century saw considerably more hurricanes than the last half: 11.8 per decade vs. 9.4 per decade. Ditto for intense hurricanes of category 3 on the Saffir-Simpson storm scale: 4.8 vs. 3.6. In fact, the numbers of *all* hurricanes and the numbers of *intense* hurricanes have *both* been trending downward since 1966, with the decade starting in 1986 exhibiting the fewest intense hurricanes of the entire century.

Liu and Fearn (1993) also studied major storms along the U.S. Gulf Coast, but over a much longer time period: the past 3500 years. Using sediment cores taken from the center of Lake Shelby in Alabama they determined that "major hurricanes of category 4 or 5 intensity directly struck the Alabama coast ... with an average recurrence interval of ~600 years," the last of which super-storms occurred around 700 years ago. They further note that "climate modeling results based on scenarios of greenhouse warming predict a 40% - 50% increase in hurricane intensities in response to warmer tropical oceans," suggestive of the likelihood that if one of these severe storms (which is now about a century overdue) were to hit the Alabama coast

again, climate alarmists would be citing its occurrence as vindication of their doomsday predictions. In reality, however, it would be nothing more than an illustration of the age-old adage that history repeats itself.

In another severe storm study, Muller and Stone (2001) examined historical data relating to tropical storm and hurricane strikes along the southeast U.S. coast from South Padre Island, Texas to Cape Hatteras, North Carolina for the 100-year period 1901-2000. The results of their analysis revealed that the temporal variability of tropical storm and hurricane strikes was "great and significant," with most coastal sites experiencing "pronounced clusters of strikes separated by tens of years with very few strikes." With respect to the climate-alarmist claim of a tendency for increased storminess during warmer El Niño years, the data just didn't cooperate. For tropical storms and hurricanes together, the authors found an average of 1.7 storms per El Niño season, 2.6 per neutral season, and 3.3 per La Niña season. For hurricanes only, the average rate of occurrence ranged from 0.5 per El Niño season to 1.7 per La Niña season.

In the interior of the United States, Changnon and Changnon (2000) examined hail-day and thunder-day occurrences over the 100-year period 1896-1995 in terms of 20-year averages obtained from records of 66 first-order weather stations distributed across the country. They found that the frequency of thunder-days peaked in the second of the five 20-year intervals, while hail-day frequency peaked in the third or middle interval. Thereafter, both parameters declined to their lowest values of the century in the final 20-year period. Hail-day occurrence, in fact, decreased to only 65% of what it was at mid-century, accompanied by a drop in national hail insurance losses over the same period.

After completing this large regional study, Changnon (2001) turned his attention to an urban and a more rural site in Chicago in an attempt to determine if there might be an urban influence on thunderstorm activity. Over the 40-year period investigated (1959-1998), he found the urban station to have experienced an average of 4.5 (12%) more thunderstorm days per year than the more rural station; and statistical tests revealed this difference to be significant at the 99% level in all four seasons of the year. In view of ongoing population growth over this period, the results of Changnon and Changnon (2000) would thus be considered, if anything, to be conservative, suggesting that the decreases in hail- and thunder-days they found for the interior of the United States over the last half of the 20th century may well have been even greater than what they determined them to be.

Also in the interior of North America, Schwartz and Schmidlin (2002) compiled a blizzard database for the years 1959-2000 for the conterminous United States. A total of 438 blizzards were identified in the 41-year record, yielding an average of 10.7 blizzards per year. Year-to-year variability was significant, with the number of annual blizzards ranging from a low of 1 in the winter of 1980/81 to a high of 27 during the winter of 1996/97. Linear regression analysis revealed a statistically significant increase in the annual number of blizzards during the 41-year period; but the total area affected by blizzards each winter remained relatively constant and showed no trend. If these observations are both correct, then average blizzard size is much smaller now than it was four decades ago. As the authors note, however, "it may also be that

the NWS is recording smaller, weaker blizzards in recent years that went unrecorded earlier in the period, as occurred also in the official record of tornadoes in the United States."

The results of this study thus suggest that -- with respect to U.S. blizzards -- frequency may possibly have increased, but if it did, intensity likely did the opposite. On the other hand, the study's authors suggest that the reported increase in blizzard frequency may well be due to an observational bias that developed over the years, for which there is a known analogue in the historical observation of tornados. That this possibility is likely a probability is suggested by the study of Gulev *et al.* (2001), who analyzed trends in Northern Hemispheric winter cyclones over essentially the same time period (1958-1999) and found a statistically significant decline of 1.2 cyclones per year using NCEP/NCAR reanalysis pressure data.

Further evidence that the blizzard frequency data are observationally-biased can be deduced from the study of Hayden (1999), who investigated storm frequencies over North America between 25° and 55°N latitude and 60° and 125°W longitude from 1885 to 1996. Over this 112-year period, Hayden reports that large regional changes in storm occurrences were observed; but when integrated over the entire geographic area, no net change in storminess was evident.

To the north, Mason and Jordan (2002) studied numerous depositional environments along the tectonically stable, unglaciated eastern Chukchi Sea coast that stretches across northwest Alaska, deriving a 6000-year record of sea level change, while simultaneously learning some interesting things about the correlation between storminess and climate in that part of the world. With respect to storminess, they learned that "in the Chukchi Sea, storm frequency is correlated with colder rather than warmer climatic conditions." Consequently, they say that their data "do not therefore support predictions of more frequent or intense coastal storms associated with atmospheric warming for this region."

Way north, Hudak and Young (2002) examined the number of fall (June-November) storms in the southern Beaufort Sea region based on criteria of surface wind speed for the relatively short period of 1970-1995. Although there was considerable year-to-year variability in the number of storms, there was no discernible trend over the 26-year period in this region of the globe where climate models predict the effects of CO<sub>2</sub>-induced global warming to be most evident.

In conclusion, as the earth has warmed over the past hundred and fifty years, during its recovery from the global chill of the Little Ice Age, there has been no significant increase in either the frequency or intensity of stormy weather in Europe and North America. In fact, most studies suggest just the *opposite* has likely occurred. This observation -- coupled with the fact that storminess in many other parts of the planet has also decreased or held steady as the world has warmed -- thus suggests there is no data-based reason to believe that storms *anywhere* will become either more frequent or more intense if the world warms a bit more in the future.

Additional information on this topic, including reviews of storms not discussed here, can be found at [http://www.co2science.org/subject/s/subject\\_s.php](http://www.co2science.org/subject/s/subject_s.php) under the heading Storms.

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### **5.7. Snow**

What can we learn about past -- and possibly future -- climate change from studies of snow? In this brief summary of pertinent research, we review this question on the basis of studies conducted in North America.

Brown (2000) employed data from Canada and the United States to reconstruct monthly snow cover properties over mid-latitude (40-60°N) regions of North America back to the early 1900s, finding evidence of what he described as "a general twentieth century increase in North American snow cover extent, with significant increases in winter (December-February) snow

water equivalent averaging 3.9% per decade." Although this finding is consistent with climate model simulations that indicate increased precipitation in response to global warming, it covers too little time to tell us much about the *cause* of modern warming.

Moore *et al.* (2002) studied a longer period of time in their analysis of a 103-meter ice core retrieved from a high elevation site on Mount Logan -- Canada's highest mountain -- which is located in the heavily-glaciated Saint Elias region of the Yukon. From this deep core, as well as from some shallow coring and snow-pit sampling, they derived a snow accumulation record that extended over *three* centuries (from 1693 to 2000), which indicated that heavier snow accumulation at their study site was generally associated with warmer tropospheric temperatures over northwestern North America.

So what does their record reveal? Over its first half, there is no significant trend in the snow accumulation data. From 1850 onward, however, there is a positive trend that is significant at the 95% confidence level, which indicates that recovery from the cold conditions of the Little Ice Age began in the mid-1800s, *well before there was a large enough increase in the air's CO<sub>2</sub> concentration for that greenhouse gas to have been responsible for the first part of the century-and-a-half-long warming.* This finding is further strengthened by the temperature reconstruction of Esper *et al.* (2002), which places the start of modern warming at about the same time as that suggested by Moore *et al.*'s snow data, contradicting the temperature record of Mann *et al.* (1998, 1999), which puts the beginning of the modern warming trend at about 1910.

The results of other snow studies raise even more unsettling questions about climate-alarmist contentions. Cowles *et al.* (2002), for example, analyzed *snow water equivalent* (SWE) data obtained from four different measuring systems -- snow courses, snow telemetry, aerial markers and airborne gamma radiation -- at more than 2000 sites in the eleven westernmost states of the conterminous USA over the period 1910-1998, finding that the long-term SWE trend of the region was *negative*, indicative of *declining* winter precipitation. In addition, they report that their results "reinforce more tenuous conclusions made by previous authors," citing Chagnon *et al.* (1993) and McCabe and Legates (1995), who studied snow course data from 1951-1985 and 1948-1987, respectively, at 275 and 311 sites, and who *also* found a decreasing trend in SWE at most sites in the Pacific Northwest.

Four years later, Julander and Bricco (2006) reported that snowpack data were being consistently used as indicators of global warming, and that it was thus *essential* that individuals doing so quantify, as best they could, all other influences imbedded in their data. That meeting this requirement is no trivial undertaking is indicated by their statement that "snow data may be impacted by site physical changes, vegetation changes, weather modification, pollution, sensor changes, changes in transportation or sampling date, comparisons of snow course to SNOTEL data, changes in measurement personnel or recreational and other factors," including sensors that "do not come back to zero at the end of the snow season." In an analysis of 134 sites (some having pertinent data stretching back to at least 1912), they thus selected fifteen long-term Utah snow courses representing complete elevational and geographic coverage of

the dominant snowpacks within the state and adjusted them for the major known site conditions impacting the data, after which the adjusted data for the period 1990-2005 were "compared to earlier portions of the historic record to determine if there were statistically significant differences in snowpack characteristics, particularly those that could indicate the impacts of global warming."

Of the fifteen sites studied in greatest detail, the two researchers found that seven of them exhibited *increased* snowpack in recent years, while eight exhibited *decreased* snow accumulation. They also report that "six of the seven sites with increases have significant vegetative or physical conditions leading us to believe that the impacts associated with this analysis are overstated." The ultimate conclusion of Julander and Bricco, therefore, was that "any signature of global warming currently present in the snowpack data of Utah is not yet at a level of statistical significance ... and will likely be very difficult to isolate from other causes of snowpack decline."

Results that tell much the same type of story were obtained by Bartlett *et al.* (2005), who strove to determine what changes might have occurred in the mean onset date of snow and its yearly duration in North America over the period 1950-2002, based on data for the contiguous United States that come from the 1062 stations of the U.S. Historical Climatology Network, data for Canada that come from the 3785 stations of the Canadian Daily Climate Dataset, and data for Alaska that come from the 543 stations of the National Weather Service cooperative network in that state. As a result of their efforts, the three researchers found that "for the period 1961-1990 the mean snow onset date in North America [was] 15 December, with mean snow cover duration of 81 days." In addition, they report there were "no significant trends in either onset or duration from 1950 to 2002." Nevertheless, interannual variations of as much as 18 and 15 days in onset and duration, respectively, were present in the data; but for both parameters they report that "no net trend was observed."

We find it to be extremely interesting that from 1950 to 2002, during which time the air's CO<sub>2</sub> concentration rose by fully 20% (from approximately 311 to 373 ppm), there was *no net change* in either the mean *onset* or *duration* of snow cover for *the entire continent of North America*; and to provide some context for this 62-ppm increase in atmospheric CO<sub>2</sub> concentration, we note that it is essentially *identical* to the mean difference between the highs and lows of the three *interglacials* and *glacials* reported by Siegenthaler *et al.* (2005) for the period prior to 430,000 years ago. Surely, one would expect that such a change should have made *some* impact on North American snow cover, unless, of course, atmospheric CO<sub>2</sub> enrichment has *far* less impact on climate than what climate alarmists claim it does.

In a somewhat different type of study, i.e., that of winter weather *variability*, which climate alarmists typically depict as becoming more extreme in response to global warming, Woodhouse (2003) generated a tree-ring based reconstruction of SWE for the Gunnison River basin of western Colorado that spans the period 1569-1999. This work revealed, in her words, that "the twentieth century is notable for several periods that *lack* [our italics] extreme years."

Specifically, she reports that "the twentieth century is notable for several periods that contain few or no extreme years, for both low and high SWE extremes."

Also addressing the subject of extreme winter weather was Lawson (2003), who examined meteorological records for information pertaining to the occurrence and severity of blizzards within the Prairie Ecozone of western Canada. Over the period 1953-1997, no significant trends were found in central and eastern locations. However, there was a significant *downward* trend in blizzard frequency in the western prairies; and Lawson remarks that "this trend is consistent with results found by others that indicate a decrease in cyclone frequency over western Canada." He also notes that the blizzards that do occur there "exhibit no trend in the severity of their individual weather elements." These findings, in his words, "serve to illustrate that the changes in extreme weather events anticipated under Climate Change may not always be for the worse."

Likewise concentrating on blizzards were Schwartz and Schmidlin (2002), who examined past issues of *Storm Data* -- a publication of the U.S. National Weather Service (NWS) -- to compile a blizzard database for the years 1959-2000 for the conterminous United States. This effort resulted in a total of 438 blizzards being identified in the 41-year record, yielding an average of 10.7 blizzards per year; and linear regression analysis revealed a statistically significant increase in the annual number of blizzards during the 41-year period. However, the total *area* affected by blizzards each winter remained relatively constant; and if these observations are both correct, average blizzard size must have decreased over the four-decade period. On the other hand, as the researchers note, "it may also be that the NWS is recording smaller, weaker blizzards in recent years that went unrecorded earlier in the period, as occurred also in the official record of tornadoes in the United States."

Yet another blizzard study was conducted by Changnon and Changnon (2006), who analyzed the spatial and temporal distributions of damaging snowstorms and their economic losses by means of property-casualty insurance data pertaining to "highly damaging storm events, classed as catastrophes by the insurance industry, during the 1949-2000 period." This work indicated, as they describe it, that "the incidence of storms peaked in the 1976-1985 period," but that snowstorm incidence "exhibited no up or down trend during 1949-2000." The two researchers thus concluded their paper by stating that "the temporal frequency of damaging snowstorms during 1949-2000 in the United States does not display any increase over time, indicating that either no climate change effect on cyclonic activity has begun, or if it has begun, altered conditions have not influenced the incidence of snowstorms."

Last of all, Gulev *et al.* (2001) used sea level pressure taken from NCEP/NCAR reanalysis data for the period 1958-1999 to develop a Northern Hemispheric winter (January-March) climatology of cyclones (storms) that reached a sea level pressure of 1000 mb or lower. Linear trend estimates based on these data revealed a statistically significant (95% level) annual decline of 1.2 cyclones per year, suggesting that there were 50 *fewer* winter cyclones at the end of the study period than at its beginning. Additional analyses suggested that the Northern Hemisphere winter cyclones were intensifying at quicker rates and reaching greater maximum depths (lower

sea level pressure) at the end of the record than they were at its beginning. However, the wintertime cyclones were also experiencing shorter life cycles at the end of the 42-year period, dissipating more quickly than at its beginning.

Could these changes be the result of global warming? According to the three scientists, they are probably connected to large-scale features of atmospheric variability, such as the North Atlantic Oscillation and the North Pacific Oscillation. As for the large decrease reported in the annual number of Northern Hemisphere cyclones over the 42-year period, we note that this observation is in *direct opposition* to climate-alarmist predictions, which suggest that the frequency of such events will *increase* as a result of global warming. Once again, therefore, the results of climate model simulations appear to be diametrically opposed to the testimony of nature.

In conclusion, snow and snowstorm data from North America provide no support for the climate-alarmist claims that (1) modern global warming did not commence until after 1910, (2) this warming has been primarily driven by anthropogenic greenhouse gas emissions, and (3) its continuance will lead to more frequent and more extreme weather phenomena, including windstorms and precipitation, which in winter equate to *blizzards* and *snowfall*. Real-world data just don't support their contentions.

Additional information on this topic, including reviews on snow not discussed here, can be found at [http://www.co2science.org/subject/s/subject\\_s.php](http://www.co2science.org/subject/s/subject_s.php) under the heading Snow.

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### **5.8. Storm Surges**

One of the many aspects of climate catastrophism that are said by climate alarmists to be sure to occur in response to CO<sub>2</sub>-induced global warming is the heaving of the world's seas beyond their normal bounds in more frequent and increasingly violent *storm surges*. We here investigate this claim via a brief summarization of the findings of a number of pertinent papers we have reviewed on our website, looking for evidence of the predicted changes over the course of the supposedly unprecedented warming of the past century, and particularly the past

quarter-century, relative to what occurred over prior periods stretching back in time from a few decades to a few millennia.

De Lange and Gibb (2000) analyzed trends in sea level data obtained from several tide gauges located within Tauranga Harbor, New Zealand, over the period 1960-1998. In studying seasonal, interannual and decadal distributions of storm surge data, they discovered a considerable *decline* in the annual *number* of storm surge events in the latter half of the nearly four-decade-long record. A similar trend was noted in the *magnitude* of storm surges. In addition, maximum water levels, including tides, also declined over the past two decades.

Decadal variations in the data were linked to both the Inter-decadal Pacific Oscillation (IPO) and the El Niño-Southern Oscillation (ENSO), with La Niña events producing more storm surge days than El Niño events. In addition, wavelet analyses of annual storm surge frequency data indicated that before 1978 the frequency "was enhanced by the IPO, and subsequently it has been attenuated." Clearly, these findings are just the *opposite* of what climate alarmists are continually trying to scare us into believing.

Pirazzoli (2000) analyzed tide-gauge and meteorological (wind and atmospheric pressure) data for the slightly longer period of 1951-1997 along the northern portion of the Atlantic coast of France. This effort revealed that the number of atmospheric depressions (storms) and strong surge winds in this region "are becoming less frequent" and that "ongoing trends of climate variability show a decrease in the frequency and hence the gravity of coastal flooding." Because these findings, too, are just the opposite of what is being preached by radical environmentalists, Pirazzoli suggests that they should be "reassuring," especially for those concerned about coastal flooding.

Stretching out the timeframe just a bit more, Raicich (2003) analyzed 62 years of sea-level data for the period 1 July 1939 to 30 June 2001 at Trieste, in the Northern Adriatic, in an attempt to determine historical trends of positive and negative surge anomalies. This work led to the discovery that weak and moderate positive surges did not exhibit any definite trends, while *strong* positive surges clearly became *less* frequent over the period of study, *even in the face of a gradually rising sea level*, "presumably," in Raicich's words, "as a consequence of a general weakening of the atmospheric activity," which was likewise found by Pirazzoli to be the case for Brittany.

Based on data for the somewhat longer period of 1901-1990, Wroblewski (2001) determined there was a linear increase in mean annual sea level at the southern Baltic seaport of Kolobrzeg of  $12 \pm 2$  cm per century. Over this same period, however, there was *no* trend in annual sea level *maxima*. Two high values stood out above the rest in the 1980s, but two similar spikes occurred in the 1940s; and there were half a dozen comparable high values in the first two decades of the record. In light of the slow upward trend in *mean* sea level, therefore, it is extremely surprising that annual *maximum* sea levels due to storm surges did not likewise rise over the past century. One can only conclude that these events must have become less intense over the same time interval.

Utilizing a full century of data, Zhang *et al.* (2000) analyzed ten very long records of storm surges derived from hourly tide gauge measurements made along the east coast of the United States, in order to calculate indexes of count, duration and integrated intensity of surge-producing storms that provide objective, quantitative and comprehensive measures of historical storm activities in this region. The end result of their comprehensive undertaking was a demonstrable lack of "any discernible long-term secular trend in storm activity during the twentieth century," which finding, in their words, "suggests a lack of response of storminess to minor global warming along the U.S. Atlantic coast during the last 100 years."

Looking considerably further back in time, Woodworth and Blackman (2002) analyzed four discontinuous sets of high-water data from the UK's Liverpool waterfront that span the period 1768-1999, looking for changes in annual maximum high water (tide plus surge), surge at annual maximum high water (surge component of annual maximum high water), and annual maximum surge-at-high-water. In doing so, they could detect no significant trends in the first two parameters over the period of study; but they found that the annual maximum surge-at-high-water actually *declined*, and at a rate of  $0.11 \pm 0.04$  meters per century, which finding suggests that the winds responsible for producing high storm surges were much stronger and/or more common during the early part of the record (Little Ice Age) than during the latter part (Modern Warm Period).

Last of all, in what is by far the longest look back in time of the papers treating this subject, Nott and Hayne (2001) produced a 5000-year record of tropical cyclone frequency and intensity along a 1500-km stretch of coastline in northeastern Australia located between latitudes 13 and 24°S by (1) geologically dating and topographically surveying landform features left by surges produced by historic hurricanes and (2) running numerical models to estimate storm surge and wave heights necessary to reach the landform locations. This work revealed that several "super-cyclones" with central pressures less than 920 hPa and wind speeds in excess of 182 kilometers per hour had occurred over the past 5000 years at intervals of roughly 200 to 300 years in all parts of the region of study. The two researchers also report that the Great Barrier Reef "experienced at least five such storms over the past 200 years, with the area now occupied by Cairns experiencing two super-cyclones between 1800 and 1870." The 20th century, however, was *totally devoid* of such storms, "with only one such event (1899) since European settlement in the mid-nineteenth century."

In light of the findings of these several studies, it seems safe to conclude that storm surges around the world have not responded to rising temperatures in the way climate alarmists continue to claim they should, even in the face of what they describe as the most dramatic global warming of the past two millennia. Storm surges have definitely *not* increased in either frequency or magnitude. In the majority of cases investigated, in fact, they have actually tended to decrease.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/o/oceanstormsurge.php>.



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## **5.9. Temperature Variability**

Another negative consequence typically claimed by the climate alarmists to results from CO<sub>2</sub>-induced global warming is a concomitant increase in *climatic variability*, including more frequent and severe weather events, such as storms, floods and droughts, as well as more extreme values of meteorological variables, such as precipitation and maximum and minimum air temperature. In this section, we explore some of the wealth of evidence that stands as a testimony *against* this claim as it pertains to *temperature variability*.

We begin with the long view of the subject provided by the study of Oppo *et al.* (1998), who studied sediments from Ocean Drilling Project site 980 on the Feni Drift (55.5°N, 14.7°W) in the North Atlantic. Working with a core pertaining to the period from 500,000 to 340,000 years ago, they analyzed  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  obtained from benthic foraminifera and  $\delta^{18}\text{O}$  obtained from planktonic foraminifera to develop histories of deep water circulation and sea surface temperature (SST), respectively. In doing so, they discovered a number of persistent climatic oscillations with periods of 6000, 2600, 1800 and 1400 years that traversed the entire length of the sediment core record, extending through glacial and interglacial epochs alike. These SST variations, which were found to be in phase with deep-ocean circulation changes, were on the order of 3°C during cold glacial maxima but only 0.5 to 1°C during warm interglacials.

Similar results were obtained by McManus *et al.* (1999), who also examined a half-million-year-old deep-sea sediment core from the eastern North Atlantic. Significant SST oscillations were again noted throughout the record, and they too were of much greater amplitude during glacial periods (4 to 6°C) than during interglacials (1 to 2°C). Likewise, in another study of a half-million-year-long sediment core from the same region, Helmke *et al.* (2002) found that the most stable of all climates held sway during what they called "peak interglaciations" or *periods of greatest warmth*. In this regard, we note that the temperatures of *all four* of the interglacials that preceded the one in which we currently live were *warmer* than the present one, and by an average temperature *in excess of 2°C*, as determined by Petit *et al.* (1999). Hence, even if the earth were to continue its recent (and possibly ongoing) recovery from the global chill of the Little Ice Age, that warming would likely not only *not* lead to greater temperature variability, as suggested by climate alarmists, but rather to a state of *reduced* temperature variability, as evidenced by real-world data pertaining to the past half million years.

Shifting our focus to the past millennium, Cook *et al.* (2002) report the results of a tree-ring study of long-lived silver pines on the West Coast of New Zealand's South Island. The chronology they derived provides a reliable history of Austral summer temperatures from AD 1200 to 1957, after which measured temperatures were used to extend the history to 1999. Cook *et al.* say their reconstruction indicates "there have been several periods of above and below average temperature that have not been experienced in the 20th century." This finding indicates that New Zealand temperatures grew *less* variable over the 20th century, when the world's climate alarmists claim the planet warmed at a rate that was *unprecedented* over all of the earlier cooler period of *greater* temperature variability, in clear contradiction of their claim that temperatures become more variable when it warms.

Also contradicting climate-alarmist dogma are the findings of Manrique and Fernandez-Cancio (2000). These scientists employed a network of approximately 1000 samples of tree-ring series representative of a significant part of Spain to reconstruct thousand-year chronologies of temperature and precipitation, after which they used this data base to identify anomalies in these parameters that varied from their means by more than four standard deviations. In doing so, they found that the greatest concentration of extreme climatic excursions, which they describe as "the outstanding oscillations of the Little Ice Age," occurred between AD 1400 and 1600, during a period when extreme low temperatures reached their maximum frequency.

In yet another part of the world, many long tree-ring series obtained from widely-spaced Himalayan cedar trees were used by Yadav *et al.* (2004) to develop a temperature history of the western Himalayas for the period AD 1226-2000. "Since the 16th century," to use their words, "the reconstructed temperature shows higher variability as compared to the earlier part of the series (AD 1226-1500), reflecting unstable climate during the Little Ice Age (LIA)." With respect to this greater variability of climate during colder conditions, they note that similar results have been obtained from juniper tree-ring chronologies from central Tibet (Braeuning, 2001), and that "historical records on the frequency of droughts, dust storms and floods in China also show that the climate during the LIA was highly unstable (Zhang and Crowley, 1989)." Likewise, in a

study of the winter half-year temperatures of a large part of China, Ge *et al.* (2003) also identified greater temperature anomalies during the 1600s than in the 1980s and 90s.

Focusing on just the past century, Rebetez (2001) analyzed day-to-day variability in two temperature series from Switzerland over the period 1901-1999, during which time the two sites experienced temperature increases of 1.2 and 1.5°C. Their work revealed that warmer temperatures led to a *reduction* in temperature variability at both locations. As they describe it, "warmer temperatures are accompanied by a general reduction of variability, both in daily temperature range and in the monthly day-to-day variability." Hence, we see that even on this much finer time scale, it is *cooling*, not warming (as climate alarmists claim), that brings an increase in temperature variability.

In a study based on daily maximum (max), minimum (min) and mean air temperatures (T) from 1062 stations of the U.S. Historical Climatology Network, Robeson (2002) computed the slopes of the relationships defined by plots of daily air temperature standard deviation vs. daily mean air temperature for each month of the year for the period 1948-1997. This protocol revealed, in Robeson's words, that "for most of the contiguous USA, the slope of the relationship between the monthly mean and monthly standard deviation of daily Tmax and Tmin - the variance response - is either negative or near-zero," which means, as they describe it, that "for most of the contiguous USA, a warming climate should produce either reduced air-temperature variability or no change in air-temperature variability." He also reports that the negative relationships are "fairly strong, with typical reductions in standard deviation ranging from 0.2 to 0.5°C for every 1°C increase in mean temperature."

In Canada, according to Shabbar and Bonsal (2003), "extreme temperature events, especially those during winter, can have many adverse environmental and economic impacts." Hence, they chose to examine trends and variability in the frequency, duration, and intensity of winter (Jan-Mar) cold and warm spells during the second half of the 20th century. From 1950-1998, they found that western Canada experienced *decreases* in the frequency, duration and intensity of winter cold spells. In the east, however, distinct *increases* in the frequency and duration of winter cold spells occurred. With respect to winter warm spells, significant increases in both their frequency and duration were observed across most of Canada, with the exception of the extreme northeastern part of the country, where warm spells appear to be becoming shorter and less frequent. In the mean, therefore, there appear to be close-to-compensating trends in the frequency and intensity of winter cold spells in different parts of Canada, while winter warm spells appear to be increasing somewhat. As a result, Canada *appears* to have experienced a *slight* amelioration of extreme winter weather over the past half-century.

In another study that suffers from the difficulty of having but a few short decades of data to analyze, Iskenderian and Rosen (2000) studied two mid-tropospheric temperature data sets spanning the last forty years, calculating day-to-day variability within each month, season and year. Averaged over the entire Northern Hemisphere, they found that mid-tropospheric temperature variability exhibited a slight upward trend since the late 1950s in one of the data sets; but, as they note, "this trend is significant in the spring season only." They also admit that

"the robustness of this springtime trend is in doubt," because the trend obtained from the other data set was negative. For the conterminous United States, however, the two data sets both showed "mostly small positive trends in most seasons." But, again, none of these trends were statistically significant. Therefore, Iskenderian and Rosen acknowledge that they "cannot state with confidence that there has been a change in synoptic-scale temperature variance in the mid-troposphere over the United States since 1958."

In an attempt to determine the role that might have been played by the planet's *mean* temperature in influencing temperature *variability* over the latter half of the 20th century, Higgins *et al.* (2002) examined the influence of two important sources of Northern Hemispheric climate variability - the El Niño/Southern Oscillation (ENSO) and the Arctic Oscillation - on winter (Jan-Mar) daily temperature extremes over the conterminous United States from 1950 to 1999. With respect to the Arctic Oscillation, there was basically no difference in the number of extreme temperature days between its positive and negative phases. With respect to the ENSO phenomenon, however, Higgins *et al.* found that during El Niño years, the total number of extreme temperature days was found to *decrease* by around 10%, while during La Niña years they *increased* by around 5%. With respect to winter temperatures across the conterminous United States, therefore, the climate-alarmist contention that warmer global temperatures - such as are typically experienced during El Niño years - will produce more extreme weather conditions is found to be false. In this study, in fact, just the *opposite* was found to be true.

Over the same time period, Zhai and Pan (2003) derived trends in the frequencies of warm days and nights, cool days and nights, and hot days and frost days for the whole of China, based on daily surface air temperature data obtained from approximately 200 weather observation stations scattered across the country. Over the period of record, and especially throughout the 1980s and 90s, there were increases in the numbers of warm days and nights, while there were decreases in the numbers of cool days and nights, consistent with an overall increase in mean daily temperature. At the extreme *hot* end of the temperature spectrum, however, the authors report that "the number of days with daily maximum temperature above 35°C showed a slightly decreasing trend for China as a whole," while at the extreme *cold* end of the spectrum, the number of frost days with daily minimum temperature below 0°C declined at the remarkable rate of 2.4 days per decade.

In considering this entire body of research, it is evident that air temperature variability almost always *decreases* when mean air temperature *rises*, be it in cases of temperature change over tens of thousands of years or over mere decades, or even between individual cooler and warmer years when different ENSO states are considered. Hence, it should be clear to all that the climate-alarmist claim that global warming will lead to more extremes of climate and weather, including more extremes of temperature itself, is just plain false.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/e/extremetemp.php>.

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### **5.10. Fires**

As stated in the EPA's Technical Support Document (TSD) to the ANPR, "general climate warming encourages wildfires by extending the summer period that dries fuels, promoting easier ignition and faster spread." In support of this statement, the TSD cites the IPCC and references therein, providing examples of observed changes in U.S. wildfire size and frequency in the recent past. But how universal are such occurrences and does the rest of the world follow suit with similar trends? Below, we briefly review the results of several analyses that evaluate the global warming/increased fire claim, concluding with a recent satellite study that evaluates the globe as a whole.

Carcaillet *et al.* (2001) developed high-resolution charcoal records from laminated sediment cores extracted from three small kettle lakes located within the mixed-boreal and coniferous-boreal forest region of eastern Canada, after which they determined whether vegetation change or climate change was the primary determinant of changes in fire frequency, comparing their fire history with hydro-climatic reconstructions derived from  $\delta^{18}\text{O}$  and lake-level data. Throughout the Climatic Optimum of the mid-Holocene, between about 7000 and 3000 years ago, when it was significantly warmer than it is today, they report that "fire intervals were double those in the last 2000 years," meaning fires were only half as frequent throughout the earlier warmer period as they were during the subsequent cooler period. They also determined that "vegetation does not control the long-term fire regime in the boreal forest," but that "climate appears to be the main process triggering fire." In addition, they report that "dendroecological studies show that both frequency and size of fire decreased during the 20th century in both west (e.g. Van Wagner, 1978; Johnson *et al.*, 1990; Larsen, 1997; Weir *et al.*, 2000) and east Canadian coniferous forests (e.g. Cwynar, 1997; Foster, 1983; Bergeron, 1991; Bergeron *et al.*, 2001), possibly due to a drop in drought frequency and an increase in long-term annual precipitation (Bergeron and Archambault, 1993)." These several findings thus led them to conclude that a "future warmer climate is likely to be less favorable for fire ignition and spread in the east Canadian boreal forest than over the last 2 millennia," which is good news for Canada and similar parts of the world.

In another Canadian study that sheds important new light on this subject, four forest scientists investigated "regional fire activity as measured by the decadal proportion of area burned and the frequency of fire years vs. non-fire years in the Waswanipi area of northeastern Canada

[49.5-50.5°N, 75-76.5°W], and the long-term relationship with large-scale climate variations ... using dendroecological sampling along with forest inventories, aerial photographs, and ecoforest maps." The results of their investigation revealed that instead of the interval of time between wildfires *shortening* as time progressed and the climate warmed -- as was implied by a CRD and repeated in the TSD to have been almost universal for North America -- there was "a major *lengthening* [our italics] of the fire cycle." How *major*? There was a lengthening, in their words, "from 99 years before 1940 to 282 years after 1940." In addition, the four researchers note that "in the context of the past 300 years, many regional fire regimes of the Canadian boreal forest, as reconstructed from dendroecological analysis, experienced a decrease in fire frequency after 1850 [or the "end of the Little Ice Age," as they describe it] (Bergeron and Archambault, 1993; Larsen, 1996) and a further decrease after 1940 (Bergeron *et al.*, 2001, 2004a,b, 2006)."

In further study of this subject, Lauzon *et al.* investigated the fire history of a 6480-km<sup>2</sup> area located in the Baie-Des-Chaleurs region of Gaspesie at the southeastern edge of Quebec, "using Quebec Ministry of Natural Resource archival data and aerial photographs combined with dendrochronological data." Results indicated that coincident with the 150-year warming that led to the demise of the Little Ice Age and the establishment of the Current Warm Period, there was "an increase in the fire cycle from the pre-1850 period (89 years) to the post-1850 period (176 years)," and that "both maximum and mean values of the Fire Weather Index decreased statistically between 1920 and 2003," during which period "extreme values dropped from the *very high* to *high* categories, while mean values changed from *moderate* to *low* categories." In this particular part of the world, therefore, 20th-century global warming has led to a significant decrease in the frequency of forest fires, as weather conditions conducive to their occurrence have gradually become less prevalent and extreme.

Pitkanen *et al.* (2003) constructed a Holocene fire history of dry heath forests in eastern Finland on the basis of charcoal layer data obtained from two small mire basins and fire scars on living and dead pine trees. This work revealed a "decrease in fires during climatic warming in the Atlantic chronozone (about 9000-6000 cal. yr. BP)," prompting them to conclude that "the very low fire frequency during the Atlantic chronozone *despite climatic warming with higher summer temperatures* [our italics], is contrary to assumptions about possible implications of the present climatic warming due to greenhouse gasses."

Thereafter, the researchers observed an increase in fire frequency at the transition between the Atlantic and Subboreal chronozones around 6000 cal. yr. BP, noting that "the climatic change that triggered the increase in fire frequency was cooling and a shift to a more continental climate." In addition, they report that the data of Bergeron and Archambault (1993) and Carcaillet *et al.* (2001) from Canada suggest much the same thing, i.e., less boreal forest fires during periods of greater warmth. Consequently, "as regards the concern that fire frequency will increase in [the] near future owing to global warming," the researchers say their data "suggest that fires from 'natural' causes (lightening) are not likely to increase significantly in eastern Finland and in geographically and climatically related areas."

Back in Canada, citing a number of climate-alarmist predictions of what could happen there, Girardin *et al.* (2006) introduced their study of the subject by writing that "human-induced climate change could lead to an increase in forest fire activity in Ontario, owing to the increased frequency and severity of drought years, increased climatic variability and incidence of extreme climatic events, and increased spring and fall temperatures," noting that "climate change therefore could cause longer fire seasons (Wotton and Flannigan, 1993), with greater fire activity and greater incidence of extreme fire activity years (Colombo *et al.*, 1998; Parker *et al.*, 2000)." Consequently, to see if any of these negative prognostications might have recently come to pass, they reconstructed a history of area burned within the province of Ontario for the period AD 1781-1982 from 25 tree-ring width chronologies obtained from various sites throughout the province, spurred on, perhaps, by the increase in area burned within Ontario that is known to have occurred from 1970 through 1981 (Podur *et al.*, 2002).

So what did they find?

The three researchers report that "while in recent decades area burned has increased, it remained below the level recorded prior to 1850 and particularly below levels recorded in the 1910s and 1920s," noting further that "the most recent increase in area burned in the province of Ontario was preceded by the period of lowest fire activity ever estimated for the past 200 years (1940s-1960s)." Consequently, although they say that, *according to theory*, "one should expect greater area burned in a changing climate," especially one that is driven by anthropogenic-induced increases in atmospheric CO<sub>2</sub> concentration, their findings revealed no support for this contention. In fact, they revealed just the *opposite*.

In another study that analyzed the relationship between climate change and wildfire occurrence in considerable detail, Schoennagel *et al.* investigated "climatic mechanisms influencing subalpine forest fire occurrence in western Colorado, which provide a key to the intuitive link between drought and large, high-severity fires that are keystone disturbance processes in many high-elevation forests in the western United States," focusing on three major climatic oscillations: the El Niño Southern Oscillation (ENSO), the Pacific Decadal Oscillation (PDO) and the Atlantic Multidecadal Oscillation (AMO).

Results of this analysis revealed that "fires occurred during short-term periods of significant drought and extreme cool (negative) phases of ENSO and PDO and during positive departures from [the] mean AMO index," while "at longer time scales, fires exhibited 20-year periods of synchrony with the cool phase of the PDO, and 80-year periods of synchrony with extreme warm (positive) phases of the AMO." In addition, they say that "years of combined positive AMO and negative ENSO and PDO phases represent 'triple whammies' that significantly increased the occurrence of drought-induced fires." On the other hand, they write that "drought and wildfire are associated with warm phases of ENSO and PDO in the Pacific Northwest and northern Rockies while the opposite occurs in the Southwest and southern Rockies," citing the findings of Westerling and Swetnam (2003), McCabe *et al.* (2004) and Schoennagel *et al.* (2005). Thus, it is easy to see that climatic influences on western U.S. wildfires are definitely much more complex than what is suggested by simplistic climate-



alarmist claims; and Schoennagel *et al.* thus conclude "there remains considerable uncertainty regarding the effects of CO<sub>2</sub>-induced warming at regional scales." Nevertheless, they report "there is mounting evidence that the recent shift to the positive phase of the AMO will promote higher fire frequencies" in the region of their study, i.e., high-elevation western U.S. forests; but the body of their work clearly suggests that such a consequence should certainly *not* be viewed as a response to CO<sub>2</sub>-induced global warming, either real or imagined.

A *contrary* example, where warming *does* appear to enhance fire occurrence, is provided by Pierce *et al.* (2004), who dated fire-related sediment deposits in alluvial fans in central Idaho, USA, in a research program designed to reconstruct Holocene fire history in xeric ponderosa pine forests and to look for links to past climate change. This endeavor focused on tributary alluvial fans of the South Fork Payette (SFP) River area, where fans receive sediment from small but steep basins in weathered batholith granitic rocks that are conducive to post-fire erosion. Altogether, they obtained 133 AMS <sup>14</sup>C-derived dates from 33 stratigraphic sites in 32 different alluvial fans. In addition, they compared their findings with those of Meyer *et al.* (1995), who had earlier reconstructed a similar fire history for nearby Yellowstone National Park in Wyoming, USA.

Pierce *et al.*'s work revealed, in their words, that "intervals of stand-replacing fires and large debris-flow events are largely coincident in SFP ponderosa pine forests and Yellowstone, most notably during the 'Medieval Climatic Anomaly' (MCA), ~1,050-650 cal. yr BP." What is more, they note that "in the western USA, the MCA included widespread, severe multidecadal droughts (Stine, 1998; Woodhouse and Overpeck, 1998), with increased fire activity across diverse northwestern conifer forests (Meyer *et al.*, 1995; Rollins *et al.*, 2002)."

Following the Medieval Warm Period and its frequent large-event fires was the Little Ice Age, when, as Pierce *et al.* describe it, "colder conditions maintained high canopy moisture, inhibiting stand-replacing fires in both Yellowstone lodgepole pine forests and SFP ponderosa pine forests (Meyer *et al.*, 1995; Rollins *et al.*, 2002; Whitlock *et al.*, 2003)." Subsequently, however, they report that "over the twentieth century, fire size and severity have increased in most ponderosa pine forests," which they suggest may be largely due to "the rapidity and magnitude of twentieth-century global climate change."

With respect to their central thesis, which appears to be well supported by both the SFP and Yellowstone data, we agree with Pierce *et al.* that both the size and severity of large-event stand-replacing fires tend to increase with increasing temperature in the part of the world and for the specific forests they studied; and we note that the Yellowstone data also depict a sharp drop in large-event fire frequency and severity during the earlier Dark Ages Cold Period, which followed on the heels of the preceding peak in such fires that was concomitant with the still earlier Roman Warm Period.

Also working in the United States, and coming to much the same general conclusion, were Westerling *et al.* (2006), who compiled a comprehensive database of large wildfires in western United States forests since 1970 and compared it to hydro-climatic and land-surface data. Their

findings are succinctly summarized by Running (2006) in an accompanying Perspective, wherein he writes that "since 1986, longer warmer summers have resulted in a fourfold increase of major wildfires and a sixfold increase in the area of forest burned, compared to the period from 1970 to 1986," noting also that "the length of the active wildfire season in the western United States has increased by 78 days, and that the average burn duration of large fires has increased from 7.5 to 37.1 days." In addition, he notes that "four critical factors - earlier snowmelt [by one to four weeks], higher summer temperatures [by about 0.9°C], longer fire season, and expanded vulnerable area of high-elevation forests - are combining to produce the observed increase in wildfire activity."

So what is the case for the *world as a whole*, i.e., what is the *net result* of the often *opposite* wildfire responses to warming that are typical of different parts of the planet?

This question was recently explored by Riano *et al.* (2007), who conducted "an analysis of the spatial and temporal patterns of global burned area with the Daily Tile US National Oceanic and Atmospheric Administration-Advanced Very High-Resolution Radiometer Pathfinder 8 km Land dataset between 1981 and 2000." For several areas of the world, this effort revealed there were indeed significant upward trends in land area burned. Some parts of Eurasia and western North America, for example, had annual upward trends as high as 24.2 pixels per year, where a pixel represents an area of 64 km<sup>2</sup>. These *increases* in burned area, however, were offset by equivalent *decreases* in burned area in tropical southeast Asia and Central America. Consequently, in the words of Riano *et al.*, "there was no significant global annual upward or downward trend in burned area." In fact, they say "there was also no significant upward or downward global trend in the burned area for any individual month." In addition, they say that "latitude was not determinative, as divergent fire patterns were encountered for various land cover areas at the same latitude."

Consequently, although one can readily identify specific parts of the planet that have experienced both significant increases and decreases in land area burned over the last two to three decades of the 20th century, as we have done in the materials reviewed above, *for the globe as a whole* there was absolutely *no* relationship between global warming and total area burned over this latter period, during which time it is claimed the world warmed at a rate and to a degree that were both unprecedented over the past several millennia. Clearly, the TSD and IPCC have strongly overplayed the degree of risk between future temperature and wildfire incidence.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/f/firegw.php>.

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## 6. BIOLOGICAL EFFECTS OF CO<sub>2</sub>

### **6.1. Plant Productivity Responses**

Perhaps the best known consequence of the rise in atmospheric CO<sub>2</sub> is the stimulation of plant productivity. This growth enhancement occurs because, at a fundamental level, carbon dioxide is the basis of almost all life on Earth, serving as the primary raw material utilized by plants to produce the organic matter out of which they construct their tissues. Consequently, the more CO<sub>2</sub> there is in the air, the better plants grow, which *fact* has been confirmed in literally thousands of laboratory and field studies.

Over the past decade, our organization, the Center for the Study of Carbon Dioxide and Global Change, has amassed the largest database in the world detailing that fact. To date, we have archived *thousands* of results from *hundreds* of peer-reviewed research studies conducted by *hundreds* of researchers. Our archive is available free of charge on the Internet at [http://www.co2science.org/data/plant\\_growth/plantgrowth.php](http://www.co2science.org/data/plant_growth/plantgrowth.php). There, we list the photosynthetic and dry weight responses of plants growing in CO<sub>2</sub>-enriched air, arranged by scientific or common plant name. We also provide the full peer-reviewed journal reference and the experimental conditions in which the study was conducted for each individual record.

Because of the enormous amount of data contained in our database, it is impossible for us to present the bulk of that data here. Therefore, we have elected to only provide a brief review of a selected handful of herbaceous and woody plants, which findings, nonetheless, represent typical responses for such plants. For information on a particular plant not included below, please consult our online database.

#### **6.1.1 Herbaceous plants**

A 300 ppm increase in the air's CO<sub>2</sub> content typically raises the productivity of most herbaceous plants by about one-third (Cure and Acock, 1986; Mortensen, 1987); and this positive response occurs in plants that utilize all three of the major biochemical pathways (C<sub>3</sub>, C<sub>4</sub>, CAM) of photosynthesis (Poorter, 1993). Thus, with more CO<sub>2</sub> in the air, the productivity of nearly all crops rises, as they produce more branches and tillers, more and thicker leaves, more extensive root systems, and more flowers and fruit (Idso, 1989). On average, a 300 ppm increase in atmospheric CO<sub>2</sub> enrichment leads to yield increases of 15% for CAM crops, 49% for C<sub>3</sub> cereals, 20% for C<sub>4</sub> cereals, 24% for fruits and melons, 44% for legumes, 48% for roots and tubers and 37% for vegetables (Idso and Idso, 2000). It should come as no surprise, therefore, that the father of modern research in this area – Sylvan H. Wittwer – has stated that “it should be considered good fortune that we are living in a world of gradually increasing levels of atmospheric CO<sub>2</sub>,” and that “the rising level of atmospheric CO<sub>2</sub> is a universally free premium, gaining in magnitude with time, on which we can all reckon for the future.”

Additional information on this topic, including reviews of herbaceous plants not discussed here, can be found at [http://www.co2science.org/subject/a/subject\\_a.php](http://www.co2science.org/subject/a/subject_a.php) under the heading Agriculture.

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### 6.1.1.1. Alfalfa

What are some of the ways in which the C<sub>3</sub> legume alfalfa (*Medicago sativa* L.) responds to atmospheric CO<sub>2</sub> enrichment? The papers reviewed below deal with this important forage crop and reveal a variety of positive phenomena.

Morgan *et al.* (2001) grew alfalfa for 20 days post-defoliation in growth chambers maintained at atmospheric CO<sub>2</sub> concentrations of 355 and 700 ppm and low or high levels of soil nitrogen to see how these factors affected plant regrowth. They determined that the plants in the elevated CO<sub>2</sub> treatment attained total dry weights over the 20-day regrowth period that were 62% greater than those reached by the plants grown in ambient air, irrespective of soil nitrogen concentration.

De Luis *et al.* (1999) grew alfalfa plants in controlled environment chambers in air of 400 and 700 ppm CO<sub>2</sub> for two weeks before imposing a two-week water treatment on them, wherein the soil in which half of the plants grew was maintained at a moisture content approaching field capacity while the soil in which the other half grew was maintained at a moisture content that was only 30% of field capacity. Under these conditions, the CO<sub>2</sub>-enriched water-stressed plants displayed an average water-use efficiency that was 2.6 and 4.1 times greater than that of the water-stressed and well-watered plants, respectively, growing in ambient 400-ppm-CO<sub>2</sub> air. In addition, under ambient CO<sub>2</sub> conditions, the water stress treatment increased the mean plant root:shoot ratio by 108%, while in the elevated CO<sub>2</sub> treatment it increased it by 269%. As a result, the nodule biomass on the roots of the CO<sub>2</sub>-enriched water-stressed plants was 40 and 100% greater than the nodule biomass on the roots of the well-watered and water-stressed plants, respectively, growing in ambient air. Hence, the CO<sub>2</sub>-enriched water-stressed plants acquired 31 and 97% more total plant nitrogen than the well-watered and water-stressed

plants, respectively, growing in ambient air. The bottom line, in terms of productivity, was that the CO<sub>2</sub>-enriched water-stressed plants attained 2.6 and 2.3 times more total biomass than the water-stressed and well-watered plants, respectively, grown at 400 ppm CO<sub>2</sub>.

Luscher *et al.* (2000) grew effectively- and ineffectively-nodulating (good nitrogen-fixing vs. poor nitrogen-fixing) alfalfa plants in large FACE plots for multiple growing seasons at atmospheric CO<sub>2</sub> concentrations of 350 and 600 ppm, while half of the plants in each treatment received a high supply of soil nitrogen and the other half received only minimal amounts of this essential nutrient. The extra CO<sub>2</sub> increased the yield of *effectively*-nodulating plants by about 50%, regardless of soil nitrogen supply, while it actually caused a 25% yield *reduction* in *ineffectively*-nodulating plants subjected to low soil nitrogen, yet produced an intermediate yield stimulation of 11% for the same plants under conditions of high soil nitrogen, which suggests that the ability to symbiotically fix nitrogen is an important factor in eliciting strong positive growth responses to elevated CO<sub>2</sub> under conditions of low soil nitrogen supply.

Sgherri *et al.* (1998) grew alfalfa in open-top chambers at ambient (340 ppm) and enriched (600 ppm) CO<sub>2</sub> concentrations for twenty-five days, after which water was withheld for five additional days so they could investigate the interactive effects of elevated CO<sub>2</sub> and water stress on plant water status, leaf soluble protein and carbohydrate content, and chloroplast thylakoid membrane composition. They found that the plants grown in elevated CO<sub>2</sub> exhibited the best water status during the moisture deficit part of the study, as indicated by leaf water potentials that were approximately 30% higher (less negative) than those observed in plants grown in ambient CO<sub>2</sub>. This beneficial adjustment was achieved by partial closure of leaf stomata and by greater production of nonstructural carbohydrates (a CO<sub>2</sub>-induced enhancement of 50% was observed), both of which phenomena can lead to decreases in transpirational water loss, the former by guard cells physically regulating stomatal apertures to directly control the exodus of water from leaves, and the latter by nonstructural carbohydrates influencing the amount of water available for transpiration. This latter phenomenon occurs because many nonstructural carbohydrates are osmotically active solutes that chemically associate with water through the formation of hydrogen bonds, thereby effectively reducing the amount of unbound water available for bulk flow during transpiration. Under water-stressed conditions, however, the CO<sub>2</sub>-induced difference in total leaf nonstructural carbohydrates disappeared. This may have resulted from an increased mobilization of nonstructural carbohydrates to roots in the elevated CO<sub>2</sub> treatment, which would decrease the osmotic potential in that part of the plant, thereby causing an increased influx of soil moisture into the roots. If this did indeed occur, it would also contribute to a better overall water status of CO<sub>2</sub>-enriched plants during drought conditions.

The plants grown at elevated CO<sub>2</sub> also maintained greater leaf chlorophyll contents and lipid to protein ratios, especially under conditions of water stress. Leaf chlorophyll content, for example, decreased by a mere 6% at 600 ppm CO<sub>2</sub>, while it plummeted by approximately 30% at 340 ppm, when water was withheld. Moreover, leaf lipid contents in plants grown with atmospheric CO<sub>2</sub> enrichment were about 22 and 83% higher than those measured in plants grown at ambient CO<sub>2</sub> during periods of ample and insufficient soil moisture supply,



respectively. Furthermore, at elevated CO<sub>2</sub> the average amounts of unsaturation for two of the most important lipids involved in thylakoid membrane composition were approximately 20 and 37% greater than what was measured in plants grown at 340 ppm during times of adequate and inadequate soil moisture, respectively. The greater lipid contents observed at elevated CO<sub>2</sub>, and their increased amounts of unsaturation, may allow thylakoid membranes to maintain a more fluid and stable environment, which is critical during periods of water stress in enabling plants to continue photosynthetic carbon uptake. These effects are so important, in fact, that some researchers have suggested that adaptive plant responses such as these may allow plants to better cope with *any* altered environmental condition that produces stress.

In view of these many positive effects of atmospheric CO<sub>2</sub> enrichment upon the growth and development of alfalfa plants, one can only hope that the air's CO<sub>2</sub> content continues to rise, as we will need all the help we can get from it to be able to feed the world's still-increasing number of people in the years and decades ahead.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/a/agriculturealfalfa.php>.

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### 6.1.1.2. Cotton

As the CO<sub>2</sub> content of the air increases, cotton (*Gossypium hirsutum* L.) plants typically display enhanced rates of photosynthetic carbon uptake, as noted by Reddy *et al.* (1999), who reported that twice-ambient atmospheric CO<sub>2</sub> concentrations boosted photosynthetic rates of cotton by 137 to 190% at growth temperatures ranging from 2°C below ambient to 7°C above ambient.

Elevated CO<sub>2</sub> also enhances total plant biomass and harvestable yield. Reddy *et al.* (1998), for example, reported that plant biomass at 700 ppm CO<sub>2</sub> was enhanced by 31 to 78% at growth temperatures ranging from 20 to 40°C, while boll production was increased by 40%. Similarly, Tischler *et al.* (2000) found that a doubling of the atmospheric CO<sub>2</sub> concentration increased seedling biomass by at least 56%.

These results indicate that elevated CO<sub>2</sub> concentrations tend to ameliorate the negative effects of heat stress on productivity and growth in cotton. In addition, Booker (2000) discovered that elevated CO<sub>2</sub> reduced the deleterious effects of elevated ozone on leaf biomass and starch production.

Atmospheric CO<sub>2</sub> enrichment can also induce changes in cotton leaf chemistry that tend to increase carbon sequestration in plant litter and soils. Booker *et al.* (2000), for example, observed that litter produced from cotton plants grown at 720 ppm CO<sub>2</sub> decomposed at rates that were 10 to 14% slower than those displayed by ambiently-grown plants; and after three years of exposure to air containing 550 ppm CO<sub>2</sub>, Leavitt *et al.* (1994) reported that 10% of the organic carbon present in soils beneath CO<sub>2</sub>-enriched FACE plots resulted from the extra CO<sub>2</sub> supplied to them.

In summary, as the CO<sub>2</sub> content of the air increases, it would seem to be a good bet that cotton plants will display greater rates of photosynthesis and biomass production, which should lead to greater boll production in this important fiber crop, even under conditions of elevated air temperature and ozone concentration. In addition, carbon sequestration in fields planted to cotton should also increase with future increases in the air's CO<sub>2</sub> content.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/a/agriculturecotton.php>.

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### 6.1.1.3. Maize

Nearly all agricultural species respond to increases in the air's CO<sub>2</sub> content by displaying enhanced rates of photosynthesis and biomass production. In this section, we briefly review some of the impacts of these and other related phenomena as they pertain to corn (*Zea mays* L.) or maize as it is often called.

Maroco *et al.* (1999) grew maize plants for 30 days in plexiglass chambers maintained at either ambient or triple-ambient concentrations of atmospheric CO<sub>2</sub> to determine the effects of elevated CO<sub>2</sub> on the growth of this important agricultural C<sub>4</sub> species. This exercise revealed that elevated CO<sub>2</sub> (1100 ppm) increased maize photosynthetic rates by about 15% relative to those measured in plants grown at 350 ppm CO<sub>2</sub>, in spite of the fact that both rubisco and PEP-carboxylase were down-regulated. This increase in carbon fixation likely contributed to the 20% greater biomass accumulation observed in the CO<sub>2</sub>-enriched plants. In addition, leaves of CO<sub>2</sub>-enriched plants contained approximately 10% fewer stomates per unit leaf area than leaves of control plants; and atmospheric CO<sub>2</sub> enrichment reduced stomatal conductance by as much as 71% in elevated-CO<sub>2</sub>-grown plants. As a result of these several different phenomena, the higher atmospheric CO<sub>2</sub> concentration greatly increased the intrinsic water-use efficiency of the CO<sub>2</sub>-enriched plants.

In a study designed to examine the effects of elevated CO<sub>2</sub> under *real-world field conditions*, Leakey *et al.* (2004) grew maize out-of-doors at the SoyFACE facility in the heart of the United States Corn Belt, while exposing different sections of the field to atmospheric CO<sub>2</sub> concentrations of either 354 or 549 ppm. The crop was grown, in the words of the researchers, using cultural practices deemed "typical for this region of Illinois," during a year that turned out to have experienced summer rainfall that was "very close to the 50-year average for this site, indicating that the year was not atypical or a drought year." Then, on five different days during the growing season (11 and 22 July, 9 and 21 August, and 5 September), they measured diurnal patterns of photosynthesis, stomatal conductance and microclimatic conditions.

Contrary to what many people had long assumed would be the case for a C<sub>4</sub> crop such as corn growing under even the *best* of natural conditions, Leakey *et al.* found that "growth at elevated CO<sub>2</sub> significantly increased leaf photosynthetic CO<sub>2</sub> uptake rate by up to 41%." The greatest whole-day increase was 21% (11 July) followed by 11% (22 July), during a period of low rainfall. Thereafter, however, during a period of greater rainfall, there were no significant differences between the photosynthetic rates of the plants in the two CO<sub>2</sub> treatments, so that over the entire growing season, the CO<sub>2</sub>-induced increase in leaf photosynthetic rate averaged 10%.

Additionally, on all but the first day of measurements, stomatal conductance was significantly lower (-23% on average) under elevated CO<sub>2</sub> compared to ambient CO<sub>2</sub>, which led to reduced transpiration rates in the CO<sub>2</sub>-enriched plants on those days as well; and since "low soil water availability and high evaporative demand can both generate water stress and inhibit leaf net

CO<sub>2</sub> assimilation in C<sub>4</sub> plants," they state that the lower stomatal conductance and transpiration rate they observed under elevated CO<sub>2</sub> "may have counteracted the development of water stress under elevated CO<sub>2</sub> and prevented the inhibition of leaf net CO<sub>2</sub> assimilation observed under ambient CO<sub>2</sub>."

The ultimate implication of their research, in the words of Leakey *et al.*, was that "contrary to expectations, this US Corn Belt summer climate appeared to cause sufficient water stress under ambient CO<sub>2</sub> to allow the ameliorating effects of elevated CO<sub>2</sub> to significantly enhance leaf net CO<sub>2</sub> assimilation." Hence, they concluded that "this response of *Z. mays* to elevated CO<sub>2</sub> indicates the potential for greater future crop biomass and harvestable yield across the US Corn Belt."

Also germane to this subject and supportive of the above conclusion are the effects of elevated CO<sub>2</sub> on *weeds associated with corn*. Conway and Toenniessen (2003), for example, speak of maize in Africa being attacked by the parasitic weed *Striga hermonthica*, which sucks vital nutrients from its roots, as well as from the roots of many other C<sub>4</sub> crops of the semi-arid tropics, including sorghum, sugar cane and millet, plus the C<sub>3</sub> crop rice, particularly throughout much of Africa, where *Striga* is one of the region's most economically important parasitic weeds. Here, too, materials archived on our website describe how atmospheric CO<sub>2</sub> enrichment greatly reduces the damage done by this devastating weed [see, for example, Watling and Press (1997) and Watling and Press (2000)].

Baczek-Kwinta and Koscielniak (2003) studied yet another phenomenon that is impacted by atmospheric CO<sub>2</sub> enrichment and that can affect the productivity of maize. Noting the tropical origin of maize and that the crop "is extremely sensitive to chill (temperatures 0-15°C)," they report that it is nevertheless often grown in cooler temperate zones because of its high yield potential. In such circumstances, however, maize can experience a variety of maladies associated with exposure to periods of low air temperature. Hence, to see if elevated CO<sub>2</sub> either exacerbates or ameliorates this problem, they grew two hybrid genotypes - KOC 9431 (chill-resistant) and K103xK85 (chill-sensitive) - from seed in air of either ambient (350 ppm) or elevated (700 ppm) CO<sub>2</sub> concentration (AC or EC, respectively), after which they exposed the plants to air of 7°C for eleven days, whereupon they let them recover for one day in ambient air of 20°C, all the while measuring several physiological and biochemical parameters pertaining to the plants' third fully-expanded leaves.

The two researchers' protocol revealed that "EC inhibited chill-induced depression of net photosynthetic rate (PN), especially in leaves of chill-resistant genotype KOC 9431," which phenomenon "was distinct not only during chilling, but also during the recovery of plants at 20°C." In fact, they found that "seedlings subjected to EC showed 4-fold higher PN when compared to AC plants." They also determined that "EC diminished the rate of superoxide radical formation in leaves in comparison to the AC control." In addition, they found that leaf membrane injury "was significantly lower in samples of plants subjected to EC than AC." Last of all, they report that enrichment of the air with CO<sub>2</sub> successfully inhibited the decrease in the maximal quantum efficiency of photosystem 2, both after chilling and during the one-day

recovery period. And in light of all of these positive effects of elevated CO<sub>2</sub>, they concluded that "the increase in atmospheric CO<sub>2</sub> concentration seems to be one of the protective factors for maize grown in cold temperate regions."

But what about the effects of *climate change*, both past and possibly future, on corn production? For nine areas of contrasting environment within the Pampas region of Argentina, Magrin *et al.* (2005) evaluated changes in climate over the 20th century along with changes in the yields of the region's chief crops. Then, after determining upward low-frequency trends in yield due to technological improvements in crop genetics and management techniques, plus the aerial fertilization effect of the historical increase in the air's CO<sub>2</sub> concentration, annual yield anomalies and concomitant climatic anomalies were calculated and used to develop relations describing the effects of changes in precipitation, temperature and solar radiation on crop yields, so that the effects of long-term changes in these climatic parameters on Argentina agriculture could be determined.

Noting that "technological improvements account for most of the observed changes in crop yields during the second part of the 20th century," which totaled 110% for maize, Magrin *et al.* report that due to changes in climate between the periods 1950-70 and 1970-99, maize yields increased by 18%. As a result, it can be appreciated that late 20th-century climate change, which is claimed by climate alarmists to have been *unprecedented over the past two millennia* and is often described by them as *one of the greatest threats ever to be faced by humanity*, has definitely *not* been a problem for corn cultivation in Argentina. In fact, it has actually helped it.

Much the same has been found to be true in Alberta, Canada, where Shen *et al.* (2005) derived and analyzed long-term (1901-2002) temporal trends in the agroclimate of the region. They report, for example, that "an earlier last spring frost, a later first fall frost, and a longer frost-free period are obvious all over the province." They also found that May-August precipitation in Alberta increased 14% from 1901 to 2002, and that annual precipitation exhibited a similar increasing trend, with most of the increase coming in the form of low-intensity events. In addition, the researchers note that "the area with sufficient corn heat units for corn production, calculated according to the 1973-2002 normal, has extended to the north by about 200-300 km, when compared with the 1913-32 normal, and by about 50-100 km, when compared with the 1943-72 normal."

In light of these findings, Shen *et al.* conclude that "the changes of the agroclimatic parameters imply that Alberta agriculture has benefited from the last century's climate change," emphasizing that "the potential exists to grow crops and raise livestock in more regions of Alberta than was possible in the past." They also note that the increase in the length of the frost-free period "can greatly reduce the frost risks to crops and bring economic benefits to Alberta agricultural producers," and that the northward extension of the corn heat unit boundary that is sufficient for corn production "implies that Alberta farmers now have a larger variety of crops to choose from than were available previously." Hence, they say "there is no hesitation for us to conclude that the warming climate and increased precipitation benefit agriculture in Alberta."

With respect to the future, Bootsma *et al.* (2005) derived relationships between agroclimatic indices and average yields of major grain crops, including corn, from field trials conducted in eastern Canada, after which they used them to estimate potential impacts of projected climate change scenarios on anticipated average yields for the period 2040 to 2069. Based on a range of available heat units projected by multiple General Circulation Model (GCM) experiments, they determined that average yields achievable in field trials could increase by 40 to 115% for corn, "not including the direct effect of increased atmospheric CO<sub>2</sub> concentrations." Adding expected CO<sub>2</sub> increases to the mix, along with gains in yield anticipated to be achieved through breeding and improved technology, these numbers rose to 114 to 186%.

In light of their fantastic findings, Bootsma *et al.* predict there will be a "switch to high-energy and high-protein-content crops (corn and soybeans) that are better adapted to the warmer climate." Consequently, if the GCM-based climate-change predictions prove correct, Canada will be immensely blessed by the incredible boost the changed conditions will bring to the country's agricultural productivity, and especially that of corn.

In summary, it seems fairly clear that as the air's CO<sub>2</sub> content continues to rise, and even if the climate of the world changes in the ways suggested by GCM calculations, maize plants will likely display greater rates of photosynthesis and biomass production, as well as reduced transpirational water losses and increased water-use efficiencies; and to top it all off, more areas of the world will likely become suitable for growing this important crop.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/a/agriculturemaize.php>.

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#### 6.1.1.4. Peanut

Stanciel *et al.* (2000) grew peanuts (*Arachis hypogaea* L.) hydroponically for 110 days in controlled environment chambers maintained at atmospheric CO<sub>2</sub> concentrations of 400, 800 and 1200 ppm, finding that the net photosynthetic rates of plants grown at 800 ppm CO<sub>2</sub> were 29% greater than those of plants grown at 400 ppm CO<sub>2</sub>, but that plants grown at 1200 ppm CO<sub>2</sub> displayed photosynthetic rates that were 24% lower than those exhibited by plants grown in 400-ppm CO<sub>2</sub> air. Nevertheless, the number of pods, pod weight and seed dry weight per unit area were all greater at 1200 ppm than at 400 ppm CO<sub>2</sub>. Also, harvest index, which is the ratio of seed dry weight to pod dry weight, was 19 and 31% greater at 800 and 1200 ppm CO<sub>2</sub>, respectively, than it was at 400 ppm CO<sub>2</sub>. In addition, as the atmospheric CO<sub>2</sub> concentration increased, stomatal conductance decreased, becoming 44 and 50% lower at 800 and 1200 ppm than it was at 400 ppm CO<sub>2</sub>. Thus, atmospheric CO<sub>2</sub> enrichment also reduced transpirational water loss, leading to a significant increase in plant water use efficiency.

Prasad *et al.* (2003) grew Virginia Runner (Georgia Green) peanuts from seed to maturity in sunlit growth chambers maintained at atmospheric CO<sub>2</sub> concentrations of 350 and 700 ppm and daytime-maximum/nighttime-minimum air temperatures of 32/22, 36/26, 40/30 and 44/34°C, while they assessed various aspects of vegetative and reproductive growth. In doing so, they found that leaf photosynthetic rates were unaffected by air temperature over the range investigated; but they rose by 27% in response to the experimental doubling of the air's CO<sub>2</sub> content.

Vegetative biomass, on the other hand, increased by 51% and 54% in the ambient and CO<sub>2</sub>-enriched air, respectively, as air temperature rose from 32/22 to 40/30°C. A further air temperature increase to 44/34°C, however, caused moderate to slight decreases in vegetative biomass in both the ambient and CO<sub>2</sub>-enriched air, so that the final biomass increase over the entire temperature range investigated was 27% in ambient air and 53% in CO<sub>2</sub>-enriched air.

When going from the *lowest* temperature *ambient* CO<sub>2</sub> treatment to the *highest* temperature *elevated* CO<sub>2</sub> treatment, however, there was a whopping 106% increase in vegetative biomass.

In contrast, seed yields in both the ambient and CO<sub>2</sub>-enriched air dropped dramatically with each of the three temperature increases studied, declining at the highest temperature regime to but a small percentage of what they were at the lowest temperature regime. Nevertheless, Prasad *et al.* report that "seed yields at 36.4/26.4°C under elevated CO<sub>2</sub> were similar to those obtained at 32/22°C under ambient CO<sub>2</sub>," the latter pair of which temperatures they describe as "present-day seasonal temperatures."

In light of these findings, it would appear that a warming of 4.4°C above present-day seasonal temperatures for peanut production would have essentially no effect on peanut seed yields, *as long as the atmosphere's CO<sub>2</sub> concentration rose concurrently*, by something on the order of 350 ppm. It is also important to note, according to Prasad *et al.*, that "maximum/minimum air temperatures of 32/22°C *and higher* [our italics] are *common* [our italics] in *many* [our italics] peanut-producing countries across the globe." In fact, they note that "the Anantapur district in Andhra Pradesh, which is one of the largest peanut-producing regions in India, experiences season-long temperatures *considerably greater* [our italics] than 32/22°C *from planting to maturity* [our italics]."

In light of these real-world observations, i.e., that some of the best peanut-producing regions in the world currently experience air temperatures considerably greater than what Prasad *et al.* suggest is *optimum* for peanuts (something *less* than 32/22°C), it would appear that real-world declines in peanut seed yields in response to a degree or two of warming, even in air of *ambient* CO<sub>2</sub> concentration, must be very slight *or even non-existent* (for how else could the places that commonly experience these considerably higher temperatures remain some of the best peanut-producing areas in the world?), which in turn suggests that for more realistic values of CO<sub>2</sub>-induced global warming, i.e., temperature increases on the order of 0.4°C for a doubling of the air's CO<sub>2</sub> content (Idso, 1998), there would likely be a significant *increase* in real-world peanut production.

In another pertinent study, Vu (2005) grew peanut plants from seed to maturity in greenhouses maintained at atmospheric CO<sub>2</sub> concentrations of 360 and 720 ppm and at air temperatures that were 1.5 and 6.0°C above outdoor air temperatures, while he measured a number of parameters related to the plants' photosynthetic performance. His work revealed that although Rubisco protein content and activity were down-regulated by elevated CO<sub>2</sub>, the Rubisco *photosynthetic efficiency* (the ratio of midday light-saturated carbon exchange rate to Rubisco initial or total activity) of the elevated-CO<sub>2</sub> plants "was 1.3- to 1.9-fold greater than that of the ambient-CO<sub>2</sub> plants at both growth temperatures." He also determined that "leaf soluble sugars and starch of plants grown at elevated CO<sub>2</sub> were 1.3- and 2-fold higher, respectively, than those of plants grown at ambient CO<sub>2</sub>." In addition, he discovered that the leaf transpiration of the elevated-CO<sub>2</sub> plants relative to that of the ambient-CO<sub>2</sub> plants was 12% less at near-ambient temperatures and 17% less in the higher temperature regime, while the water



use efficiency of the elevated-CO<sub>2</sub> plants relative to the ambient-CO<sub>2</sub> plants was 56% greater at near-ambient temperatures and 41% greater in the higher temperature environment.

In commenting on his findings, Vu notes that because less Rubisco protein was required by the elevated-CO<sub>2</sub> plants, the subsequent redistribution of excess leaf nitrogen "would increase the efficiency of nitrogen use for peanut under elevated CO<sub>2</sub>," just as the optimization of inorganic carbon acquisition and greater accumulation of the primary photosynthetic products in the CO<sub>2</sub>-enriched plants "would be beneficial for peanut growth at elevated CO<sub>2</sub>." Indeed, in the absence of other stresses, Vu's ultimate conclusion was that "peanut photosynthesis would perform well under rising atmospheric CO<sub>2</sub> and temperature predicted for this century."

In a somewhat different type of study, Alexandrov and Hoogenboom (2000) studied how year-to-year changes in temperature, precipitation and solar radiation had influenced the yields of peanuts over a 30-year period in the southeastern United States, after which they used the results to predict future crop yields based on climate-change output from various global circulation models (GCMs) of the atmosphere. At ambient CO<sub>2</sub> concentrations, the GCM scenarios suggested a decrease in peanut yields by the year 2020, due in part to predicted changes in temperature and precipitation. However, when the yield-enhancing effects of a doubling of the atmospheric CO<sub>2</sub> concentration were included, a totally different result was obtained: a yield *increase*.

Although we have little faith in GCM scenarios, it is interesting to note that their climate change predictions often result in positive outcomes for agricultural productivity *when the direct effects of elevated CO<sub>2</sub> on plant growth and development are included in the analyses*. These results support the findings published later in this chapter, which describe the stress-ameliorating effects of atmospheric CO<sub>2</sub> enrichment on plant growth and development under unfavorable growing conditions characterized by high air temperatures and inadequate soil moisture.

In conclusion, it would appear that even if the climate changes that are typically predicted to result from anticipated increases in the air's CO<sub>2</sub> content were to materialize, the concurrent rise in the air's CO<sub>2</sub> concentration should *more than compensate* for any deleterious effects those changes in climate might otherwise have had on the growth and yield of peanuts.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/a/peanut.php>.

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#### 6.1.1.5. Potato

In the study of Sicher and Bunce (1999), exposure to twice-ambient atmospheric CO<sub>2</sub> concentrations enhanced rates of net photosynthesis in potato plants (*Solanum tuberosum* L.) by 49%; while in the study of Schapendonk *et al.* (2000), a doubling of the air's CO<sub>2</sub> content led to an 80% increase in net photosynthesis. In a study that additionally considered the role of the air's vapor pressure deficit (VPD), Bunce (2003) found that exposure to twice-ambient atmospheric CO<sub>2</sub> concentrations boosted net photosynthesis by 36% at a VPD of 0.5 kPa (moist air) but by 70% at a VPD of 3.5 kPa (dry air). Yet another complexity was investigated by Olivo *et al.* (2002), who assessed the effect of a doubling of the air's CO<sub>2</sub> content on the net photosynthetic rates of high-altitude (*Solanum curtilobum*) and low-altitude (*S. tuberosum*) and found the rate of the former to be enhanced by 56% and that of the latter by 53%. In addition, although they did not directly report photosynthetic rates, Louche-Tessandier *et al.* (1999) noted that photosynthetic acclimation was reduced in CO<sub>2</sub>-enriched plants that were inoculated with a fungal symbiont, which consequently allowed them to produce greater amounts of biomass than non-inoculated control plants grown in ambient air.

Because elevated CO<sub>2</sub> concentrations stimulate photosynthesis in potatoes, it is only to be expected they would also increase potato biomass production. And so they do. Miglietta *et al.* (1998), for example, reported that potatoes grown at 660 ppm CO<sub>2</sub> produced 40% more tuber biomass than control plants grown in ambient air. Such reports are common, in fact, with twice-ambient atmospheric CO<sub>2</sub> concentrations having been reported to produce yield increases of 25% (Lawson *et al.*, 2001), 36% (Chen and Setter, 2003), 37% (Schapendonk *et al.*, 2000), 40% (Olivo *et al.*, 2002), 44% (Sicher and Bunce, 1999), 85% (Olivo *et al.*, 2002) and 100% (Ludewig *et al.*, 1998).

A few studies have been conducted at even higher atmospheric CO<sub>2</sub> concentrations. Kauder *et al.* (2000), for example, grew plants for up to seven weeks in controlled environments receiving an extra 600 ppm CO<sub>2</sub>, obtaining final tuber yields that were 30% greater than those of ambiently-grown plants. Also, in a study of potato microcuttings grown for four weeks in environmental chambers maintained at ambient air and air enriched with an extra 1200 ppm CO<sub>2</sub>, Pruski *et al.* (2002) found that the average number of nodes per stem was increased by 64%, the average stem dry weight by 92%, and the average shoot length by 131%.

Atmospheric CO<sub>2</sub> enrichment also leads to reductions in transpirational water loss by potato plants. Magliulo *et al.* (2003), for example, grew potatoes in the field within FACE rings maintained at either ambient (370 ppm) or enriched (550 ppm) atmospheric CO<sub>2</sub> concentrations for two consecutive years, finding that the CO<sub>2</sub>-enriched plants used 12% less water than the ambient-treatment plants, while they produced 47% more tuber biomass. Hence, the CO<sub>2</sub>-enriched plants experienced a 68% increase in *water use efficiency*, or the amount of biomass produced per unit of water used in producing it. Likewise, Olivo *et al.* (2002) found that a doubling of the air's CO<sub>2</sub> content increased the instantaneous water-use efficiencies of high-altitude and low-altitude potato species by 90% and 80%, respectively.

In the final phenomenon considered here, we review the findings of three studies that evaluated the ability of atmospheric CO<sub>2</sub> enrichment to mitigate the deleterious effects of ozone pollution on potato growth. Fangmeier and Bender (2002) determined the mean tuber yield of potato as a function of atmospheric CO<sub>2</sub> concentration for conditions of ambient and high atmospheric O<sub>3</sub> concentrations, as derived from a trans-European set of experiments. At the mean ambient CO<sub>2</sub> concentration of 380 ppm, the high O<sub>3</sub> stress reduced mean tuber yield by approximately 9%. At CO<sub>2</sub> concentrations of 540 and 680 ppm, however, the high O<sub>3</sub> stress had no significant effect on tuber yield.

Much the same results were obtained by Wolf and van Oijen (2002, 2003), who used the validated potato model LPOTCO to project future European tuber yields. Under two climate change scenarios that incorporated the effects of increased greenhouse gasses on climate (i.e., increased air temperature and reduced precipitation), the model generated increases in irrigated tuber production ranging from 2,000 to 4,000 kg of dry matter per hectare across Europe, with significant reductions in the negative effects of O<sub>3</sub> pollution.

In summary, it is clear that as the CO<sub>2</sub> content of the air increases, potato plants should exhibit increases in photosynthesis, biomass production, water use efficiency and ozone pollution resistance that should significantly enhance the tuber yields of this important agricultural staple.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/a/agriculturepotato.php>.

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#### 6.1.1.6. Rice

DeCosta *et al.* (2003a) grew two crops of rice (*Oryza sativa* L.) at the Rice Research and Development Institute of Sri Lanka from January to March (the *maha* season) and from May to August (the *yala* season) in open-top chambers in air of either ambient or ambient plus 200 ppm CO<sub>2</sub>, determining that leaf net photosynthetic rates were significantly higher in the CO<sub>2</sub>-enriched chambers than in the ambient-air chambers: 51-75% greater in the *maha* season and 22-33% greater in the *yala* season. Likewise, in the study of Gesch *et al.* (2002), where one-month-old plants were maintained at either 350 ppm CO<sub>2</sub> or switched to a concentration of 700 ppm for ten additional days, the plants switched to CO<sub>2</sub>-enriched air immediately displayed large increases in their photosynthetic rates that at the end of the experiment were still 31% greater than those exhibited by unswitched control plants.

With respect to the *opposite* of photosynthesis, Baker *et al.* (2000) reported that rates of carbon loss via dark respiration in rice plants decreased with increasing nocturnal CO<sub>2</sub> concentrations. As a result, it is not surprising that in the study of Weerakoon *et al.* (2000), rice plants exposed to an extra 300 ppm of atmospheric CO<sub>2</sub> exhibited a 35% increase in mean season-long *radiation-use efficiency*, defined as the amount of biomass produced per unit of solar radiation intercepted. In light of these several observations, therefore, one would logically expect rice plants to routinely produce more biomass at elevated levels of atmospheric CO<sub>2</sub>. *And they do.*

In conjunction with the study of DeCosta *et al.* (2003a), DeCosta *et al.* (2003b) found that CO<sub>2</sub>-enriched rice plants produced more leaves per hill, more tillers per hill, more total plant biomass, greater root dry weight, more panicles per plant and had harvest indices that were increased by 4% and 2%, respectively, in the *maha* and *yala* seasons, which suite of benefits led to ultimate grain yield increases of 24% and 39% in those two periods. In another study, Kim *et al.* (2003) grew rice crops from the seedling stage to maturity at atmospheric CO<sub>2</sub> concentrations of ambient and ambient plus 200 ppm using FACE technology and three levels of applied nitrogen -- low (LN, 4 g N m<sup>-2</sup>), medium (MN, 8 and 9 g N m<sup>-2</sup>), and high (HN, 15 g N m<sup>-2</sup>) -- for three cropping seasons (1998-2000). They found that "the yield response to elevated CO<sub>2</sub> in crops supplied with MN (+14.6%) or HN (+15.2%) was about twice that of crops supplied with LN (+7.4%)," confirming the importance of N availability to the response of rice to atmospheric CO<sub>2</sub> enrichment that had previously been determined by Kim *et al.* (2001) and Kobaysahi *et al.* (2001).

Various environmental stresses, however, can significantly alter the impact of elevated CO<sub>2</sub> on rice. In the study of Tako *et al.* (2001), for example, rice plants grown at twice-ambient CO<sub>2</sub> concentrations and ambient temperatures displayed no significant increases in biomass production; but when air temperatures were raised by 2°C, the CO<sub>2</sub>-enriched plants produced

22% more biomass than the plants grown in non-CO<sub>2</sub>-enriched air. In contrast, Ziska *et al.* (1997) reported that CO<sub>2</sub>-enriched rice plants grown at elevated air temperatures displayed no significant increases in biomass; but when the plants were grown at ambient air temperatures, the additional 300 ppm of CO<sub>2</sub> boosted their rate of biomass production by 40%. In light of these observations, rice growers should select cultivars that are most responsive to elevated CO<sub>2</sub> concentrations at the air temperatures likely to prevail in their locality in order to maximize their yield production in a future high-CO<sub>2</sub> world.

Water stress can also severely reduce rice production. As an example, Widodo *et al.* (2003) grew rice plants in eight outdoor, sunlit, controlled-environment chambers at daytime atmospheric CO<sub>2</sub> concentrations of 350 and 700 ppm for an entire season. In one set of chambers, the plants were continuously flooded. In another set, drought stress was imposed during panicle initiation. In another, it was imposed during anthesis; and in the last set, drought stress was imposed at both stages. The resultant drought-induced effects, according to the scientists, "were more severe for plants grown at ambient than at elevated CO<sub>2</sub>." They report, for example, that "plants grown under elevated CO<sub>2</sub> were able to maintain midday leaf photosynthesis, and to some extent other photosynthetic-related parameters, longer into the drought period than plants grown at ambient CO<sub>2</sub>."

Recovery from the drought-induced water stress was also more rapid in the elevated CO<sub>2</sub> treatment. At panicle initiation, for example, Widodo *et al.* observed that "as water was added back following a drought induction, it took more than 24 days for the ambient CO<sub>2</sub> [water]-stressed plants to recuperate in midday leaf CER, compared with only 6-8 days for the elevated CO<sub>2</sub> [water]-stressed plants." Similarly, they report that "for the drought imposed during anthesis, midday leaf CER of the elevated CO<sub>2</sub> [water]-stressed plants were fully recovered after 16 days of re-watering, whereas those of the ambient CO<sub>2</sub> [water]-stressed plants were still 21% lagging behind their unstressed controls at that date." Hence, they logically concluded that "rice grown under future rising atmospheric CO<sub>2</sub> should be better able to tolerate drought situations."

In a somewhat different type of study, Watling and Press (2000) found that rice plants growing in ambient air and infected with a root hemiparasitic angiosperm obtained final biomass values that were only 35% of those obtained by uninfected plants. In air of 700 ppm CO<sub>2</sub>, however, the infected plants obtained biomass values that were 73% of those obtained by uninfected plants. Thus, atmospheric CO<sub>2</sub> enrichment significantly reduced the negative impact of this parasite on biomass production in rice.

In summary, as the CO<sub>2</sub> concentration of the air continues to rise, rice plants will likely experience greater photosynthetic rates, produce more biomass, be less affected by root parasites, and better deal with environmental stresses, all of which effects should lead to greater grain yields.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/a/agricultureric.php>.

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#### 6.1.1.7. Sorghum

Many laboratory and field experiments have demonstrated a significant positive impact of elevated levels of atmospheric CO<sub>2</sub> on total biomass and grain production in the C<sub>4</sub> crop sorghum (*Sorghum bicolor* (L.) Moench), as may be verified by perusing the results posted within the Plant Growth (Dry Weight) section of our website. Here, we briefly summarize the findings of the subset of those studies.

Ottman *et al.* (2001) grew sorghum plants in a FACE experiment conducted near Phoenix, Arizona, USA, where plants were fumigated with air containing either 360 or 560 ppm CO<sub>2</sub> and where they were further subjected to irrigation regimes resulting in both adequate and inadequate levels of soil moisture. Averaged over the two years of their study, the extra CO<sub>2</sub> increased grain yield by only 4% in the plots receiving adequate levels of soil moisture but by fully 16% in the dry soil moisture plots.

Prior *et al.* (2005) grew sorghum in two different years in 7-meter-wide x 76-meter-long x 2-m-deep bins filled with a silt loam soil, upon which they constructed a number of clear-plastic-wall open-top chambers they maintained at ambient CO<sub>2</sub> concentrations and ambient concentrations plus 300 ppm. In the first of the two years, the extra CO<sub>2</sub> increased sorghum residue production by 14%, while in the second year it increased crop residue production by 24% and *grain* production by 22%. For a CO<sub>2</sub> increase of 200 ppm comparable to that employed in the study of Ottman *et al.*, these figures translate to crop residue increases of 9% and 16% and a grain increase of 15%.

In a review of primary research papers describing results obtained from large-scale FACE experiments conducted over the prior fifteen years, Ainsworth and Long (2005) determined that, in the mean, sorghum grain yield was increased by approximately 7% in response to a 200-ppm increase in the atmosphere's CO<sub>2</sub> concentration.

An experiment with a bit more complexity was carried out several years earlier by Watling and Press (1997), who grew sorghum with and without infection by the parasitic C<sub>3</sub> weeds *Striga hermonthica* and *S. asiatica*. The study lasted for about two months and was conducted in controlled environment cabinets fumigated with air of either 350 or 700 ppm CO<sub>2</sub>. In the absence of parasite infection, the extra 350 ppm of CO<sub>2</sub> boosted plant biomass production by 35%, which adjusted downward to make it compatible with the 200-ppm increase employed in most FACE studies corresponds to an increase of just under 21%. When infected with *S. asiatica*, the biomass stimulation provided by the extra CO<sub>2</sub> was about the same; but when infected with *S. hermonthica*, it was almost 80%, which corresponds to a similarly downward adjusted biomass increase of 45%.



In light of these several observations, it would appear that although the CO<sub>2</sub>-induced increase in total biomass and grain yield of sorghum is rather modest, ranging from 4 to 16% under well-watered conditions, it can be on the high end of this range when the plants are stressed by a shortage of water (16% has been observed) and by parasitic infection (45% has been observed). Consequently, elevated levels of atmospheric CO<sub>2</sub> seem to help sorghum most when help is most needed.

Additional information on this topic, including reviews on sorghum not discussed here, can be found at [http://www.co2science.org/subject/a/subject\\_a.php](http://www.co2science.org/subject/a/subject_a.php) under the main heading Agriculture, sub heading Sorghum.

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#### 6.1.1.8. Soybean

Wittwer (1995) reports that the common soybean (*Glycine max* L.) "provides about two thirds of the world's protein concentrate for livestock feeding, and is a valuable ingredient in formulated feeds for poultry and fish." Consequently, it is important to determine how soybeans will likely respond to rising atmospheric CO<sub>2</sub> concentrations with and without concomitant increases in air temperature and under both well-watered and water-stressed conditions. In this section we provide that information in a brief review of the results of several studies that have investigated these aspects of the subject.

Rogers *et al.* (2004) grew soybeans from emergence to grain maturity in ambient and CO<sub>2</sub>-enriched air (372 and 552 ppm CO<sub>2</sub>, respectively) at the SoyFACE facility of the University of Illinois at Urbana-Champaign, Illinois, USA, while CO<sub>2</sub> uptake and transpiration measurements were made from pre-dawn to post-sunset on seven days representative of different developmental stages of the crop. Across the growing season, they found that the mean daily integral of leaf net photosynthesis rose by 24.6% in the elevated CO<sub>2</sub> treatment, while mid-day stomatal conductance dropped by 21.9%, in response to the 48% increase in atmospheric CO<sub>2</sub>

employed in their study. With respect to photosynthesis, they additionally report "there was no evidence of any loss of stimulation toward the end of the growing season," noting that the largest stimulation actually occurred during late seed filling. Nevertheless, they say that the photosynthetic stimulation they observed was only "about half the 44.5% theoretical maximum increase calculated from Rubisco kinetics." Thus, there is an opportunity for soybeans to perhaps become even more responsive to atmospheric CO<sub>2</sub> enrichment than they are currently, which potential could well be realized via future developments in the field of genetic engineering.

Bunce (2005) grew soybeans in the field in open-top chambers maintained at atmospheric CO<sub>2</sub> concentrations of ambient and ambient +350 ppm at the Beltsville Agricultural Research Center in Maryland, USA, where net CO<sub>2</sub> exchange rate measurements were performed on a total of 16 days between 18 July and 11 September of 2000 and 2003, during flowering to early pod-filling. Over the course of this study, daytime net photosynthesis per unit leaf area was 48% greater in the plants growing in the CO<sub>2</sub>-enriched air, while nighttime respiration per unit leaf area was not affected by elevated CO<sub>2</sub>. However, because the elevated CO<sub>2</sub> increased leaf dry mass per unit area by an average of 23%, respiration *per unit mass* was significantly lower for the leaves of the soybeans growing in the CO<sub>2</sub>-enriched air, producing a sure recipe for accelerated growth and higher soybean seed yields.

Working in Australia, Japan and the United States, Ziska *et al.* (2001b) observed a recurrent diurnal pattern of atmospheric CO<sub>2</sub> concentration, whereby maximum values of 440-540 ppm occurred during a three-hour pre-dawn period that was followed by a decrease to values of 350-400 ppm by mid-morning, after which there was a slow but steady increase in the late afternoon and early evening that brought the air's CO<sub>2</sub> concentration back to its pre-dawn maximum value. In an attempt to see if the pre-dawn CO<sub>2</sub> spikes they observed impacted plant growth, they grew soybeans for one month in controlled-environment chambers under three different sets of conditions: a constant 24-hour exposure to 370 ppm CO<sub>2</sub>, a constant 370 ppm CO<sub>2</sub> exposure during the day followed by a constant 500 ppm CO<sub>2</sub> exposure at night, and a CO<sub>2</sub> exposure of 500 ppm from 2200 to 0900 followed by a decrease to 370 ppm by 1000, which was maintained until 2200, somewhat mimicking the CO<sub>2</sub> cycle they observed in nature. This program revealed that the 24-hour exposure to 370 ppm CO<sub>2</sub> and the 370-ppm-day/500-ppm-night treatments produced essentially the same results in terms of biomass production after 29 days. However, the CO<sub>2</sub> treatment that mimicked the *observed* atmospheric CO<sub>2</sub> pattern resulted in a plant biomass increase of 20%.

In a study that evaluated a whole range of atmospheric CO<sub>2</sub> concentrations, from far below ambient levels to high above them, Allen *et al.* (1998) grew soybeans for an entire season in growth chambers maintained at atmospheric CO<sub>2</sub> concentrations of 160, 220, 280, 330, 660 and 990 ppm. In doing so, they observed a consistent increase in total nonstructural carbohydrates in all vegetative components including roots, stems, petioles and especially the leaves, as CO<sub>2</sub> concentrations rose. There was, however, no overall significant effect of treatment CO<sub>2</sub> concentration on nonstructural carbohydrate accumulation in soybean reproductive components, including podwalls and seeds, which observations indicate that the higher yields

reported in the literature for soybeans exposed to elevated CO<sub>2</sub> most likely result from increases in the number of pods produced per plant, and not from the production of larger individual pods or seeds.

The increasing amounts of total nonstructural carbohydrates that were produced with each additional increment of CO<sub>2</sub> provided the raw materials to support greater biomass production at each CO<sub>2</sub> level. Although final biomass and yield data were not reported in this paper, the authors did present biomass data obtained at 66 days into the experiment. Relative to aboveground biomass measured at 330 ppm CO<sub>2</sub>, the plants that were grown in sub-ambient CO<sub>2</sub> concentrations of 280, 220 and 160 ppm exhibited 12, 33 and 60% *less* biomass, respectively, while plants grown in atmospheric CO<sub>2</sub> concentrations of 660 and 990 ppm displayed 46 and 66% *more* biomass. Hence, it is likely that soybeans began experiencing increases in total nonstructural carbohydrates and yield as the air's CO<sub>2</sub> concentration began to rise with the onset of the Industrial Revolution; and because nonstructural carbohydrate production rises incrementally with incremental increases in the CO<sub>2</sub> content of the air, soybeans will likely continue to produce ever more total nonstructural carbohydrates that will sustain ever greater yields as the CO<sub>2</sub> content of the air continues to rise in the future.

In a study of two contrasting soybean cultivars, Ziska and Bunce (2000) grew *Ripley*, which is semi-dwarf and determinate in growth, and *Spencer*, which is standard-size and indeterminate in growth, for two growing seasons in open-top chambers maintained at atmospheric CO<sub>2</sub> concentrations of ambient and ambient plus 300 ppm. Averaged over both years, the elevated CO<sub>2</sub> treatment increased photosynthetic rates in the Ripley and Spencer varieties by 76 and 60%, respectively. However, Spencer showed a greater CO<sub>2</sub>-induced increase in vegetative biomass than Ripley (132 vs. 65%). Likewise, elevated CO<sub>2</sub> enhanced seed yield in Spencer by 60% but by only 35% in Ripley, suggesting that cultivar selection for favorable yield responses to atmospheric CO<sub>2</sub> enrichment could have a big impact on future farm productivity.

In another study of contrasting types of soybeans, Nakamura *et al.* (1999) grew nodulated and non-nodulated plants in pots within controlled-environmental cabinets maintained at atmospheric CO<sub>2</sub> concentrations of 360 and 700 ppm in combination with low and high soil nitrogen supply for three weeks. They found that at low nitrogen, elevated CO<sub>2</sub> increased total plant dry mass by approximately 40 and 80% in nodulated soybeans grown at low and high nitrogen supply, respectively, while non-nodulated plants exhibited no CO<sub>2</sub>-induced growth response at low nitrogen but an approximate 60% growth enhancement at high nitrogen supply. Hence, it would appear that as the air's CO<sub>2</sub> content continues to rise, non-nodulated soybeans will only display increases in biomass if they are grown in nitrogen-rich soils. Nodulated soybeans, however, should display increased growth in both nitrogen-rich and nitrogen-poor soils, with their responses being about twice as large in high as in low soil nitrogen conditions.

In yet another study of soybeans with different genetic characteristics, Ziska *et al.* (2001a) grew one modern and eight ancestral soybean genotypes in glasshouses maintained at atmospheric CO<sub>2</sub> concentrations of 400 and 710 ppm, finding that the elevated CO<sub>2</sub> increased

photosynthetic rates in all cultivars by an average of 75%. This photosynthetic enhancement led to CO<sub>2</sub>-induced increases in seed yield that averaged 40%, except for one of the ancestral varieties that exhibited an 80% increase in seed yield. Consequently, since the air's CO<sub>2</sub> content is anticipated to continue to rise in the years and decades ahead, plant breeders would be wise to consider utilizing the highly-CO<sub>2</sub>-responsive ancestral cultivar identified in this study in future breeding programs.

To get a glimpse of what might happen if future temperatures also continue to rise, Ziska (1998) grew soybeans for 21 days in controlled environments having atmospheric CO<sub>2</sub> concentrations of approximately 360 (ambient) or 720 ppm and soil temperatures of 25 (ambient) or 30°C. He found that elevated CO<sub>2</sub> significantly increased whole plant net photosynthesis at both temperatures, with the greatest effect occurring at 30°C. As time progressed, however, this photosynthetic stimulation dropped from 50% at 13 days into the experiment to 30% at its conclusion eight days later; yet in spite of this *partial* acclimation, which was far from complete, atmospheric CO<sub>2</sub> enrichment significantly enhanced total plant dry weight at final harvest by 36 and 42% at 25 and 30°C, respectively.

Studying the complicating effects of water stress were Serraj *et al.* (1999), who grew soybeans from seed in pots within a glasshouse until they were four weeks old, after which half of the plants were subjected to an atmospheric CO<sub>2</sub> concentration of 360 ppm, while the other half were exposed to an elevated concentration of 700 ppm. In addition, half of the plants at each CO<sub>2</sub> concentration were well-watered and half of them were allowed to experience water stress for a period of 18 days. This protocol revealed that short-term (18-day) exposure of soybeans to elevated CO<sub>2</sub> significantly decreased daily and cumulative transpirational water losses compared to plants grown at 360 ppm CO<sub>2</sub>, regardless of water treatment. In fact, elevated CO<sub>2</sub> reduced total water loss by 25 and 10% in well-watered and water-stressed plants, respectively. Also, drought stress significantly reduced rates of net photosynthesis among plants of both CO<sub>2</sub> treatments. However, plants grown in elevated CO<sub>2</sub> consistently exhibited higher photosynthetic rates than plants grown at ambient CO<sub>2</sub>, regardless of soil water status.

At final harvest, the elevated CO<sub>2</sub> treatment had little effect on the total dry weight of plants grown at optimal soil moisture, but it increased the total dry weight of water-stressed plants by about 33%. Also, while root dry weight declined for plants grown under conditions of water stress and ambient CO<sub>2</sub> concentration, no such decline was exhibited by plants subjected to atmospheric CO<sub>2</sub> enrichment and water stress. As the atmospheric CO<sub>2</sub> concentration continues to rise, therefore, soybeans will likely display concurrent increases in photosynthesis and decreases in water loss. Thus, in the future, the water-use efficiency of soybeans will likely be significantly enhanced, allowing plants to better tolerate less frequent rains.

Studying *both* water and high-temperature stress were Ferris *et al.* (1999), who grew soybeans in glasshouses maintained at atmospheric CO<sub>2</sub> concentrations of 360 and 700 ppm for 52 days, before having various environmental stresses imposed on them for eight days during early seed filling. For the eight-day stress period, some plants were subjected to air temperatures that were 15°C higher than those to which the control plants were exposed, while some were

subjected to a water stress treatment in which their soil moisture contents were maintained at 40% of that experienced by the control plants. Averaged across all stress treatments and harvests, this protocol revealed that the high CO<sub>2</sub> treatment increased total plant biomass by 41%. Both high-temperature and water-deficit treatments, singly or in combination, reduced overall biomass by approximately the same degree, regardless of CO<sub>2</sub> treatment. Thus, even when the greatest biomass reductions of 17% occurred in the CO<sub>2</sub>-enriched and ambiently grown plants, in response to the combined stresses of high temperature and low soil moisture, plants grown in elevated CO<sub>2</sub> still exhibited an average biomass that was 24% greater than that displayed by plants grown in ambient CO<sub>2</sub>.

Averaged across all stress treatments and harvests, elevated CO<sub>2</sub> increased seed yield by 32%. In addition, it tended to ameliorate the negative effects of environmental stresses. CO<sub>2</sub>-enriched plants that were water stressed, for example, had an average seed yield that was 34% greater than that displayed by water-stressed controls grown at ambient CO<sub>2</sub>, while CO<sub>2</sub>-enriched plants exposed to high temperatures produced 38% more seed than their respectively stressed counterparts. In fact, the greatest relative impact of elevated CO<sub>2</sub> on seed yield occurred in response to the combined stresses of high temperature and low soil moisture, with CO<sub>2</sub>-enriched plants exhibiting a seed yield that was 50% larger than that of similarly stressed plants grown in ambient CO<sub>2</sub>.

In a predictive application of this type of knowledge, but based on a different means of obtaining it, Alexandrov and Hoogenboom (2000) studied how temperature, precipitation and solar radiation influenced soybean yields over a 30-year period in the southeastern United States, after which they used the results they obtained to predict future crop yields based on climate output from various global circulation models of the atmosphere. At ambient CO<sub>2</sub> concentrations, the model-derived scenarios pointed to a decrease in soybean yields by the year 2020, due in part to predicted changes in temperature and precipitation. However, when the yield-enhancing effects of a doubling of the air's CO<sub>2</sub> concentration were included in the simulations, a completely different projection was obtained: a yield *increase*.

Shifting to the subject of soybean seed *quality*, Caldwell *et al.* (2005) write that "the beneficial effects of isoflavone-rich foods have been the subject of numerous studies (Birt *et al.*, 2001; Messina, 1999)," and that "foods derived from soybeans are generally considered to provide both specific and general health benefits," presumably via these substances. Hence, it is only natural they would wonder how the isoflavone content of soybean seeds may be affected by the ongoing rise in the air's CO<sub>2</sub> content, and that they would conduct a set of experiments to find the answer.

The curious scientists grew well-watered and fertilized soybean plants from seed to maturity in pots within two controlled-environment chambers, one maintained at an atmospheric CO<sub>2</sub> concentration of 400 ppm and one at 700 ppm. The chambers were initially kept at a constant air temperature of 25°C. At the onset of seed fill, however, air temperature was reduced to 18°C until seed development was complete, in order to simulate average outdoor temperatures at this stage of plant development. In a second experiment, this protocol was repeated, except

that the temperature during seed fill was maintained at 23°C, with and without drought (a third treatment), while in a third experiment, seed-fill temperature was maintained at 28°C, with or without drought.

In the first experiment, where air temperature during seed fill was 18°C, the elevated CO<sub>2</sub> treatment increased the total isoflavone content of the soybean seeds by 8%. In the second experiment, where air temperature during seed fill was 23°C, the extra CO<sub>2</sub> increased total seed isoflavone content by 104%, while in the third experiment, where air temperature during seed fill was 28°C, the CO<sub>2</sub>-induced isoflavone increase was 101%. Finally, when drought-stress was added as a third environmental variable, the extra CO<sub>2</sub> boosted total seed isoflavone content by 186% when seed-fill air temperature was 23°C, while at a seed-fill temperature of 28°C, it increased isoflavone content by 38%.

Under all environmental circumstances studied, enriching the air with an extra 300 ppm of CO<sub>2</sub> increased the total isoflavone content of soybean seeds. In addition, the percent increases measured under the stress situations investigated were always greater than the percent increase measured under optimal growing conditions. Consequently, the direct effects of atmospheric CO<sub>2</sub> enrichment on the health-promoting properties of soybean seeds would appear to be universally beneficial and a boon to the entire human race, especially in light of the fact that Bernacchi *et al.* (2005) characterize the soybean as "the world's most important seed legume."

Also writing on the subject of soybean seed quality, Thomas *et al.* (2003) say "the unique chemical composition of soybean has made it one of the most valuable agronomic crops worldwide," noting that "oil and protein comprise ~20 and 40%, respectively, of the dry weight of soybean seed." Consequently, they explored the effects of elevated CO<sub>2</sub> *plus temperature* on soybeans that were grown to maturity in sunlit controlled-environment chambers with sinusoidally-varying day/night max/min temperatures of 28/18, 32/22, 36/26, 40/30 and 44/34°C and atmospheric CO<sub>2</sub> concentrations of 350 and 700 ppm. This work revealed that the effect of temperature on seed composition and gene expression was "pronounced," but that "there was no effect of CO<sub>2</sub>." In this regard, however, they note that "Heagle *et al.* (1998) observed a positive significant effect of CO<sub>2</sub> enrichment on soybean seed oil and oleic acid concentration," the latter of which parameters their own study found to rise with increasing temperature all the way from 28/18 to 44/34°C. In addition, they determined that "32/22°C is optimum for producing the highest oil concentration in soybean seed," that "the degree of fatty acid saturation in soybean oil was significantly increased by increasing temperature," and that crude protein concentration increased with temperature to 40/30°C.

In commenting on these observations, Thomas *et al.* note that "the intrinsic value of soybean seed is in its supply of essential fatty acids and amino acids in the oil and protein, respectively." Hence, we conclude that the temperature-driven changes they identified in these parameters, as well as the CO<sub>2</sub> effect observed by Heagle *et al.*, bode well for the future production of this important crop and its value to society in a CO<sub>2</sub>-enriched and warming world. Thomas *et al.* note, however, that "temperatures during the soybean-growing season in the southern USA are

at, or slightly higher than, 32/22°C," and that warming could negatively impact the soybean oil industry in this region. For the world as a whole, however, warming would be a positive development for soybean production; while in the southern United States, shifts in planting zones could readily accommodate changing weather patterns associated with this phenomenon.

In conclusion, as the air's CO<sub>2</sub> content continues to rise, soybeans will likely respond by displaying significant increases in growth and yield, with possible improvements in seed quality; and these beneficial effects will likely persist, even if temperatures rise or soil moisture levels decline, regardless of their cause.

Additional information on this topic, including reviews on sorghum not discussed here, can be found at [http://www.co2science.org/subject/a/subject\\_a.php](http://www.co2science.org/subject/a/subject_a.php) under the main heading Agriculture, sub heading Soybean.

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#### 6.1.1.9. Strawberry

In the open-top chamber study of Bunce (2001), strawberry plants (*Fragaria x ananassa*) exposed to air containing an extra 300 and 600 ppm CO<sub>2</sub> displayed photosynthetic rates that were 77 and 106% greater, respectively, than rates displayed by plants grown in ambient air containing 350 ppm CO<sub>2</sub>. Similarly, Bushway and Pritts (2002) reported that strawberry plants grown at atmospheric CO<sub>2</sub> concentrations between 700 and 1000 ppm exhibited



photosynthetic rates that were consistently more than 50% greater than rates displayed by control plants.

Because elevated CO<sub>2</sub> stimulates rates of photosynthesis in strawberry plants, it is only to be expected that it would also increase biomass production in this important agricultural species. And it does. After growing plants in air containing an additional 170 ppm CO<sub>2</sub> above ambient concentrations, Deng and Woodward (1998) reported that total fresh fruit weights were 42 and 17% greater than weights displayed by control plants receiving high and low soil nitrogen inputs, respectively. In addition, Bushway and Pritts (2002) reported that a two- to three-fold increase in the air's CO<sub>2</sub> content boosted strawberry fruit yield by 62%.

Thus, as the air's CO<sub>2</sub> content continues to rise, strawberry plants will likely exhibit enhanced rates of photosynthesis and biomass production, which should lead to greater fruit yields in this economically important agricultural crop.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/a/agriculturestraw.php>.

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### 6.1.1.10. Sunflower

As the CO<sub>2</sub> content of the air increases, sunflower plants (*Helianthus annuus* L.) will likely display enhanced rates of photosynthetic carbon uptake. In the study of Sims *et al.* (1999), for example, exposure to twice-ambient atmospheric CO<sub>2</sub> concentrations enhanced rates of net photosynthesis in individual upper-canopy sunflower leaves by approximately 50%. Similarly, Luo *et al.* (2000) reported that sunflowers grown at 750 ppm CO<sub>2</sub> displayed canopy carbon uptake rates that were fully 53% greater than those exhibited by plants grown at 400 ppm CO<sub>2</sub>.

Because elevated levels of atmospheric CO<sub>2</sub> stimulate rates of photosynthesis in sunflower plants, they should also increase biomass production in this important agricultural species. The study of Zerihun *et al.* (2000) suggests this inference is correct, as they reported that twice-ambient CO<sub>2</sub> concentrations increased whole plant biomass in sunflowers by 44, 13 and 115% when the plants were simultaneously exposed to low, medium and high levels of soil nitrogen.

In summary, it is clear that as the CO<sub>2</sub> content of the air increases, sunflower plants should exhibit enhanced rates of photosynthesis and biomass production, which should consequently lead to greater seed yields in this important agricultural crop.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/a/agriculturesun.php>.

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### 6.1.1.11. Tomato

In the study of Ziska *et al.* (2001), tomato plants (*Lycopersicon esculentum* Mill.) grown at a nocturnal atmospheric CO<sub>2</sub> concentration of 500 ppm displayed total plant biomass values that were 10% greater than those exhibited by control plants growing in air containing 370 ppm CO<sub>2</sub>. This result was likely the consequence of the elevated CO<sub>2</sub> reducing the rate of nocturnal respiration in the plants, which would have allowed them to utilize the retained carbon to produce more biomass.

This CO<sub>2</sub>-induced benefit, as well as a host of other positive effects of atmospheric CO<sub>2</sub> enrichment, are also manifest under unfavorable growing conditions. Jwa and Walling (2001), for example, reported that fungal infection reduced plant biomass in tomatoes growing in normal air by about 30%. However, in fungal-infected plants grown at twice-ambient atmospheric CO<sub>2</sub> concentrations, the elevated CO<sub>2</sub> completely ameliorated the growth-reducing effects of the pathogen.

In another stressful situation, Maggio *et al.* (2002) reported that a 500-ppm increase in the air's CO<sub>2</sub> concentration increased the average value of the root-zone salinity threshold in tomato plants by about 60%. In addition, they reported that the water-use efficiency of the CO<sub>2</sub>-enriched plants was about twice that of the ambiently-grown plants.

As the CO<sub>2</sub> content of the air increases, tomato plants will likely display greater rates of photosynthesis and biomass production, which should consequently lead to greater fruit yields, even under stressful conditions of fungal infection and high soil salinity.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/a/agriculturetomato.php>.

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### 6.1.1.12. Wheat

In one study, Dijkstra *et al.* (1999) grew winter wheat (*Triticum aestivum* L.) in open-top chambers and field-tracking sun-lit climatized enclosures maintained at atmospheric CO<sub>2</sub> concentrations of ambient and ambient plus 350 ppm CO<sub>2</sub> for two years, determining that the elevated CO<sub>2</sub> increased both final grain yield and total aboveground biomass by 19%. In another study, Masle (2000) grew two varieties of wheat for close to a month in greenhouses maintained at atmospheric CO<sub>2</sub> concentrations of 350 and 900 ppm, finding that the CO<sub>2</sub>-enriched plants exhibited biomass increases of 52 to 93%, depending upon variety and vernalization treatment.

Based on a plethora of experimental observations of this nature, many scientists developed yield prediction models for wheat. Using the output of several such models, Alexandrov and Hoogenboom (2000) estimated the impact of typically predicted climate changes on wheat production in Bulgaria in the 21st century, finding that a doubling of the air's CO<sub>2</sub> concentration would likely enhance wheat yields there between 12 and 49% *in spite of a predicted 2.9 to 4.1°C increase in air temperature*. Likewise, Eitzinger *et al.* (2001) employed the WOFOST crop model to estimate wheat production in northeastern Austria in the year 2080. For a doubled atmospheric CO<sub>2</sub> concentration with concomitant climate changes derived from five different general circulation models of the atmosphere, they obtained simulated yield increases of 30 to 55%, even in the face of predicted changes in both temperature and precipitation.

Southworth *et al.* (2002) used the CERES-Wheat growth model to calculate winter wheat production during the period 2050-2059 for ten representative farm locations in Indiana, Illinois, Ohio, Michigan and Wisconsin, USA, for six future climate scenarios. They report that some of the southern portions of this group of states would have exhibited climate-induced yield decreases had the aerial fertilization effect of the CO<sub>2</sub> increase that drove the predicted changes in climate not been included in the model. When they did include the increase in the air's CO<sub>2</sub> concentration (to a value of 555 ppm), however, they note that "wheat yields increased 60 to 100% above current yields across the central and northern areas of the study region," while in the southern areas "small increases and small decreases were found." The few minor decreases, however, were associated with the more extreme Hadley Center greenhouse

run that presumed a 1% increase in greenhouse gases per year and a doubled climate variability; hence, they would have to be considered highly unlikely to ever occur.

In discussing their findings, Southworth *et al.* note that other modeling studies have obtained similar results for other areas. They report, for example, that Brown and Rosenberg (1999) found winter wheat yields across other parts of the United States to increase "under all climate change scenarios modeled (1, 2.5, and 5°C temperature increases)," and that Cuculeanu *et al.* (1999) found modeled yields of winter wheat in southern Romania to increase by 15 to 21% across five sites. Also, they note that Harrison and Butterfield (1996) "found increased yields of winter wheat across Europe under all the climate change scenarios they modeled."

The final paper to deal with this subject that we have reviewed to this point in time is that of Van Ittersum *et al.* (2003), who performed a number of simulation experiments with the *Agricultural Production Systems Simulator (APSIM)-Nwheat* model in which they explored the implications of possible increases in atmospheric CO<sub>2</sub> concentration and near-surface air temperature for wheat production and deep drainage at three sites in Western Australia differing in precipitation, soil characteristics, nitrogenous fertilizer application rates and wheat cultivars. They first assessed the impact of the ongoing rise in the air's CO<sub>2</sub> content, finding that wheat grain yield increased linearly at a rate of 10-16% for each 100-ppm increase in atmospheric CO<sub>2</sub> concentration, with only a slight concomitant increase in deep drainage (a big win-tiny loss outcome). For a likely future CO<sub>2</sub> increase of 200 ppm, for example, increases in grain yield varied between 3 and 17% for low nitrogen fertilizer application rates and between 21 and 34% for high rates of nitrogen application, with the greatest relative yield response being found for the driest site studied.

When potential warming was factored into the picture, the results proved even better. The positive effects of the CO<sub>2</sub> increase on wheat grain yield were enhanced an extra 3-8% when temperatures were increased by 3°C in the model simulations. These yield increases were determined to result in an increased financial return to the typical Western Australian wheat farmer of 15-35%. In addition, the imposition of the simultaneous temperature increase led to a significant decline in deep drainage, producing a truly win-win situation that enhanced the average farmer's net income by an additional 10-20%. Consequently, it was determined that the CO<sub>2</sub>-induced increase in temperature predicted by the world's climate alarmists could well increase the net profitability of Western Australian wheat farmers by anywhere from 25-55%, while at the same time mitigating what van Ittersum *et al.* refer to as "one of Australia's most severe land degradation problems."

In light of these several observations, it should be clear to most everyone that in a wide variety of circumstances, atmospheric CO<sub>2</sub> enrichment significantly increases the biomass production and yield of wheat plants, thereby benefiting both wheat producers and consumers alike.

Additional information on this topic, including reviews on sorghum not discussed here, can be found at [http://www.co2science.org/subject/a/subject\\_a.php](http://www.co2science.org/subject/a/subject_a.php) under the main heading Agriculture, sub heading Wheat.

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### 6.1.2. Woody plants

The growth response of woody plants to atmospheric CO<sub>2</sub> enrichment has also been extensively studied. Ceulemans and Mousseau (1994), for example, tabulated the results of 95 separate experimental investigations related to this topic; while the review of Poorter (1993) includes 41 additional sets of pertinent results, and the two reviews of Wullschleger et al. (1995, 1997) contain 40 other sets of applicable data. When averaged together, these 176 individual woody plant experiments reveal a mean growth enhancement on the order of 50% for an approximate

doubling of the air's CO<sub>2</sub> content, which is about one and a half times as much as the response of non-woody herbaceous plants.

It is possible, however, that this larger result is still an underestimate of the capacity of trees and shrubs to respond to atmospheric CO<sub>2</sub> enrichment; for the mean duration of the 176 woody plant experiments described above was only five months, which may not have been sufficient for the long-term equilibrium effects of the CO<sub>2</sub> enrichment of the air to be manifest. In the world's longest such experiment, for example, Kimball *et al.* (2007) observed a 70% sustained increase in biomass production over the entire last decade of a 17-year long study in response to a 75% increase in the air's CO<sub>2</sub> content employed throughout the experiment. Likewise, studies of *Eldarica* pine trees conducted at the same location have revealed a similarly increasing growth response over the same length of time (Idso and Kimball, 1994).

In the subsections that follow, we highlight the results of several additional studies that have examined the growth response of woody plants to atmospheric CO<sub>2</sub> enrichment, which again, represent only a small fraction of the studies that are archived on our website in our Plant Growth Data section (see [http://www.co2science.org/data/plant\\_growth/plantgrowth.php](http://www.co2science.org/data/plant_growth/plantgrowth.php)).

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### 6.1.2.1. Aspen-Poplar

Several studies have documented the effects of elevated levels of atmospheric CO<sub>2</sub> on photosynthesis in various aspen clones (*Populus tremuloides*). In the short-term study of

Kruger *et al.* (1998), aspen seedlings grown for 70 days at atmospheric CO<sub>2</sub> concentrations of 650 ppm exhibited photosynthetic rates that were approximately 10% greater than those displayed by seedlings maintained at ambient CO<sub>2</sub> concentrations; while in the longer five-month study of Kubiske *et al.* (1998), atmospheric CO<sub>2</sub> enrichment significantly increased photosynthetic rates in four aspen genotypes, regardless of soil nitrogen status.

In an even longer 2.5-year study, Wang and Curtis (2001) also observed significant CO<sub>2</sub>-induced photosynthetic increases in two male and two female aspen clones; and when six aspen genotypes were grown in open-top chambers for 2.5 years at atmospheric CO<sub>2</sub> concentrations of 350 and 700 ppm, Curtis *et al.* (2000) reported that the elevated CO<sub>2</sub> concentrations increased rates of net photosynthesis by 128 and 31% at high and low soil nitrogen contents, respectively. In addition, in a study that only looked at air temperature effects that was conducted at ambient CO<sub>2</sub> concentrations, King *et al.* (1999) determined that increasing the air temperature from 13 to 29°C enhanced photosynthetic rates in four different aspen clones by an average of 35%.

In a FACE study, where O<sub>3</sub>-sensitive and O<sub>3</sub>-tolerant clones were grown for six months in field plots receiving 360 and 560 ppm CO<sub>2</sub> in combination with ambient and enriched (1.5 times ambient) O<sub>3</sub> levels, Noormets *et al.* (2001) reported that CO<sub>2</sub>-induced increases in photosynthetic rates were at least *maintained*, and sometimes even *increased*, when clones were simultaneously exposed to elevated O<sub>3</sub>. After an entire year of treatment exposure, in fact, Karnosky *et al.* (1999) noted that the powerful ameliorating effect of elevated CO<sub>2</sub> on ozone-induced damage was still operating strongly in this system; for O<sub>3</sub>-induced foliar damages in O<sub>3</sub>-sensitive and O<sub>3</sub>-tolerant clones were reduced from 55 and 17%, respectively, at ambient CO<sub>2</sub>, to 38 and 3%, respectively, at elevated CO<sub>2</sub>.

With respect to biomass production, Pregitzer *et al.* (2000) reported that 2.5 years of exposure to twice-ambient concentrations of atmospheric CO<sub>2</sub> increased fine-root biomass in six aspen genotypes by an average of 65 and 17% on nitrogen-rich and nitrogen-poor soils, respectively. Using this same experimental system, Zak *et al.* (2000) determined that elevated CO<sub>2</sub> enhanced total seedling biomass by 38% at high soil nitrogen and by 16% at low soil nitrogen. Similar results were reported in the two-year open-top chamber study of Mikan *et al.* (2000), who observed 50 and 25% CO<sub>2</sub>-induced increases in total seedling biomass at high and low soil nitrogen levels, respectively.

Thus, as the air's CO<sub>2</sub> content continues to increase, aspen seedlings will likely display enhanced rates of photosynthesis and biomass production, regardless of genotype, gender, O<sub>3</sub>-sensitivity, and soil nitrogen status. Consequently, greater amounts of carbon will likely be sequestered in the tissues of this most abundant of North American tree species and in the soils in which they are rooted in the years and decades ahead.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/t/treesaspen.php>.

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### 6.1.2.2. Beech

Egli and Korner (1997) rooted eight beech saplings (genus *Fagus*) directly into calcareous or acidic soils in open-top chambers and exposed them to atmospheric CO<sub>2</sub> concentrations of



either 370 or 570 ppm. Over the first year of their study, the saplings growing on calcareous soil in CO<sub>2</sub>-enriched air exhibited a 9% increase in stem diameter; and they speculated that this initial small difference may ultimately "cumulate to higher 'final' tree biomass through compounding interest."

And they were right! At the end of *three* years of differential CO<sub>2</sub> exposure, the trees in the CO<sub>2</sub>-enriched chambers were experiencing net ecosystem carbon exchange rates that were 58% greater than the rates of the trees in the ambient CO<sub>2</sub> chambers, regardless of soil type; while the stem dry mass of the CO<sub>2</sub>-enriched trees was increased by about 13% over that observed in the ambient-air chambers (Maurer *et al.*, 1999).

In a similar but much shorter experiment, Dyckmans *et al.* (2000) grew three-year-old seedlings of beech for six weeks in controlled environment chambers maintained at atmospheric CO<sub>2</sub> concentrations of 350 and 700 ppm, finding that the doubling of the air's CO<sub>2</sub> content increased seedling carbon uptake by 63%. They also noted that the majority of the assimilated carbon was allocated to the early development of leaves, which would clearly be expected to subsequently lead to greater absolute amounts of photosynthetic carbon fixation.

In the two-year study of Grams *et al.* (1999), beech seedlings grown at ambient CO<sub>2</sub> concentrations displayed large reductions in photosynthetic rates when simultaneously exposed to twice-ambient levels of ozone. However, at twice-ambient CO<sub>2</sub> concentrations, twice-ambient ozone concentrations had no negative effects on the trees' photosynthetic rates. Thus, atmospheric CO<sub>2</sub> enrichment completely ameliorated the negative effects of ozone on photosynthesis in this species.

Similarly, Polle *et al.* (1997) reported that beech seedlings grown at 700 ppm CO<sub>2</sub> for two years displayed significantly reduced activities of catalase and superoxide dismutase, which are antioxidative enzymes responsible for detoxifying highly reactive oxygenated compounds within cells. Their data imply that CO<sub>2</sub>-enriched atmospheres are conducive to less oxidative stress and, therefore, less production of harmful oxygenated compounds than typically occurs in ambient air. Consequently, the seedlings growing in the CO<sub>2</sub>-enriched air were likely able to remobilize a portion of some of their valuable raw materials away from the production of detoxifying enzymes and reinvest them into other processes required for facilitating optimal plant development and growth.

With respect to this concept of resource optimization, Duquesnay *et al.* (1998) studied the relative amounts of <sup>12</sup>C and <sup>13</sup>C in tree rings of beech growing for the past century in northeastern France and determined that the intrinsic water-use efficiency of the trees had increased by approximately 33% over that time period, no doubt in response to the concomitant rise in the air's CO<sub>2</sub> concentration over the last 100 years.

In conclusion, as the CO<sub>2</sub> content of the air increases, beech trees will likely display enhanced rates of photosynthesis and decreased damage resulting from oxidative stress. Together, these phenomena should allow greater optimization of raw materials within beech, allowing them to

produce greater amounts of biomass ever more efficiently as the atmospheric CO<sub>2</sub> concentration increases.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/t/treesbeech.php>.

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### 6.1.2.3. Birch

In the relatively short-term study of Wayne *et al.* (1998), yellow birch seedlings (*Betula pendula*) grown for two months at atmospheric CO<sub>2</sub> concentrations of 800 ppm exhibited photosynthetic rates that were about 50% greater than those displayed by control seedlings fumigated with air containing 400 ppm CO<sub>2</sub>. Similarly, in the three-month study of Tjoelker *et al.* (1998a), paper birch seedlings grown at 580 ppm CO<sub>2</sub> displayed photosynthetic rates that were approximately 30% greater than those exhibited by seedlings exposed to 370 ppm CO<sub>2</sub>. Likewise, Kellomaki and Wang (2001) reported that birch seedlings exposed to an atmospheric CO<sub>2</sub> concentration of 700 ppm for five months displayed photosynthetic rates that were about 25% greater than seedlings grown at 350 ppm CO<sub>2</sub>. Finally, in the much longer four-year study conducted by Wang *et al.* (1998), silver birch seedlings grown in open-top chambers receiving twice-ambient concentrations of atmospheric CO<sub>2</sub> displayed photosynthetic rates that were fully 110% greater than rates displayed by their ambiently-grown counterparts. Thus, short-

term photosynthetic enhancements resulting from atmospheric CO<sub>2</sub> enrichment appear to persist for several years or longer.

Because elevated CO<sub>2</sub> enhances photosynthetic rates in birch trees, it likely will also lead to increased biomass production in these important deciduous trees, as it indeed has in several experiments. In the three-month study of Tjoelker *et al.* (1998b), for example, a 57% increase in the air's CO<sub>2</sub> content increased the biomass of paper birch seedlings by 50%. When similar seedlings were grown at 700 ppm CO<sub>2</sub> for four months, Catovsky and Bazzaz (1999) reported that elevated CO<sub>2</sub> increased total seedling biomass by 27 and 130% under wet and dry soil moisture regimes, respectively. In the interesting study of Godbold *et al.* (1997), paper birch seedlings grown at 700 ppm for six months not only increased their total biomass, but also increased the number of root tips per plant by over 50%. In the longer two-year study of Berntson and Bazzaz (1998), twice-ambient levels of CO<sub>2</sub> increased the biomass of a mixed yellow and white birch mesocosm by 31%; and in another two-year study, Wayne *et al.* (1998) reported that yellow birch seedlings grown at 800 ppm CO<sub>2</sub> produced 60 and 227% more biomass than seedlings grown at 400 ppm CO<sub>2</sub> at ambient and elevated air temperatures, respectively. Finally, after exposing silver birch seedlings to twice-ambient CO<sub>2</sub> concentrations for four years, Wang *et al.* (1998) noted that CO<sub>2</sub>-enriched seedlings produced 60% more biomass than ambiently-grown seedlings. Hence, atmospheric CO<sub>2</sub> enrichment clearly enhances birch biomass in both short- and medium-term experiments.

In some studies, elevated CO<sub>2</sub> also reduced stomatal conductances in birch trees, thereby boosting their water-use efficiencies. Tjoelker *et al.* (1998a), for example, reported that paper birch seedlings grown at 580 ppm CO<sub>2</sub> for three months experienced 10-25% reductions in stomatal conductance, which contributed to 40-80% increases in water-use efficiency. Similar CO<sub>2</sub>-induced reductions in stomatal conductance (21%) were reported in silver birch seedlings grown for four years at 700 ppm CO<sub>2</sub> by Rey and Jarvis (1998).

The results of these several studies suggest that the ongoing rise in the air's CO<sub>2</sub> content will likely increase rates of photosynthesis and biomass production in birch trees, as well as improve their water use efficiencies, irrespective of any concomitant changes in air temperature and/or soil moisture status that might occur. Consequently, rates of carbon sequestration by this abundant temperate forest species should also increase in the years and decades ahead.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/t/treesbirch.php>.

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#### 6.1.2.4. Citrus Trees

How does atmospheric CO<sub>2</sub> enrichment affect the growth and development of citrus trees and the fruit they produce?

In the study of Keutgen and Chen (2001), cuttings of *Citrus madurensis* grown for three months at 600 ppm CO<sub>2</sub> displayed rates of photosynthesis that were more than 300% greater than those measured on control cuttings grown at 300 ppm CO<sub>2</sub>. In addition, elevated CO<sub>2</sub> concentrations have been shown to increase photosynthetic rates in mango (Schaffer *et al.*, 1997), mangosteen (Schaffer *et al.*, 1999) and sweet orange (Jifon *et al.*, 2002). In the study of Jifon *et al.*, it was further reported that twice-ambient CO<sub>2</sub> concentrations increased photosynthetic rates in mycorrhizal- and non-mycorrhizal-treated sour orange seedlings by 118 and 18%, respectively.

Such CO<sub>2</sub>-induced increases in photosynthesis should ultimately lead to enhanced biomass production; and so they do. Idso and Kimball (2001), for example, have documented how a 75% increase in the air's CO<sub>2</sub> content has boosted the long-term production of aboveground wood and fruit biomass in sour orange trees by 80% in a study that has been ongoing since November of 1987. Furthermore, Idso *et al.* (2002) have additionally demonstrated that the

300-ppm increase in the air's CO<sub>2</sub> content has increased the fresh weight of individual oranges by an average of 4% and the vitamin C content of their juice by an average of 5%.

In summary, these peer-reviewed studies suggest that as the air's CO<sub>2</sub> content slowly but steadily rises, citrus trees will respond by increasing their rates of photosynthesis and biomass production. In addition, they may also increase the vitamin C content of their fruit, which may help to prevent an array of human health problems brought about by insufficient intake of vitamin C.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/t/treescitrus.php>.

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#### 6.1.2.5. Eucalyptus

In the eight-month study of Roden *et al.* (1999), *Eucalyptus pauciflora* seedlings growing at 700 ppm CO<sub>2</sub> displayed seasonal rates of net photosynthesis that were approximately 30% greater than those exhibited by their ambiently-grown counterparts. In another eight-month study, Palanisamy (1999) reported that well-watered *Eucalyptus cladocalyx* seedlings exposed to 800 ppm CO<sub>2</sub> exhibited photosynthetic rates that were 120% higher than those observed in control plants growing at 380 ppm CO<sub>2</sub>. Moreover, after a one-month period of water stress,

photosynthetic rates of CO<sub>2</sub>-enriched seedlings were still 12% greater than rates displayed by ambiently-grown water-stressed seedlings.

Because elevated CO<sub>2</sub> enhances photosynthetic rates in eucalyptus species, this phenomenon should lead to increased biomass production in these rapidly growing trees. And so it does. In the eight-month experiment of Gleadow *et al.* (1998), for example, *Eucalyptus cladocalyx* seedlings growing at 800 ppm CO<sub>2</sub> displayed 134 and 98% more biomass than seedlings growing at 400 ppm CO<sub>2</sub> at low and high soil nitrogen concentrations, respectively. Similarly, *Eucalyptus pauciflora* seedlings growing at twice-ambient CO<sub>2</sub> concentrations for eight months produced 53% more biomass than control seedlings (Roden *et al.*, 1999).

In summary, as the CO<sub>2</sub> content of the air increases, eucalyptus seedlings will likely display enhanced rates of photosynthesis and biomass production, regardless of soil moisture and nutrient status. Consequently, greater amounts of carbon will likely be sequestered by this rapidly growing tree species.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/t/treeseuc.php>.

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### 6.1.2.6. Fruit-Bearing

Several studies have recently documented the effects of elevated atmospheric CO<sub>2</sub> concentrations on photosynthesis in various fruiting trees. In an eight-day experiment, Pan *et al.* (1998) found that twice-ambient CO<sub>2</sub> concentrations increased rates of net photosynthesis in one-year-old apple seedlings by 90%. In a longer three-month study, Keutgen and Chen (2001) noted that cuttings of *Citrus madurensis* exposed to 600 ppm CO<sub>2</sub> displayed rates of photosynthesis that were more than 300% greater than rates observed in control cuttings exposed to 300 ppm CO<sub>2</sub>. Likewise, in the review paper of Schaffer *et al.* (1997), it was noted that atmospheric CO<sub>2</sub> enrichment had previously been shown to enhance rates of net photosynthesis in various tropical and sub-tropical fruit trees, including avocado, banana, citrus, mango and mangosteen. Finally in the two-year study of Centritto *et al.* (1999a), cherry seedlings grown at 700 ppm CO<sub>2</sub> exhibited photosynthetic rates that were 44% greater than

those displayed by seedlings grown in ambient air, independent of a concomitant soil moisture treatment.

Because elevated CO<sub>2</sub> enhances the photosynthetic rates of fruiting trees, it should also lead to increased biomass production in them. And it does. In the two-year study of Centritto *et al.* (1999b), for example, well-watered and water-stressed seedlings growing at twice-ambient CO<sub>2</sub> concentrations displayed basal trunk areas that were 47 and 51% larger than their respective ambient controls. Similarly, in a study spanning *more than thirteen years*, Idso and Kimball (2001) demonstrated that the aboveground wood biomass of mature sour orange trees growing in air enriched with an additional 300 ppm of CO<sub>2</sub> was 80% greater than that attained by control trees growing in ambient air.

As the CO<sub>2</sub> content of the air increases, fruit trees will likely display enhanced rates of photosynthesis and biomass production, regardless of soil moisture conditions. Consequently, greater amounts of carbon will likely be sequestered in the woody trunks and branches of such species. Moreover, fruit yields may increase as well. In the study of Idso and Kimball, for example, they were stimulated to essentially the same degree as aboveground wood biomass, i.e., by 80% in response to a 75% increase in the air's CO<sub>2</sub> content.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/t/treesfruit.php>.

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#### 6.1.2.7. Nitrogen-Fixing

In the six-week study of Schortemeyer *et al.* (1999), seedlings of *Acacia melanoxylon* grown at twice-ambient atmospheric CO<sub>2</sub> concentrations displayed photosynthetic rates that were 22% greater than those of ambiently-grown seedlings. In addition, the CO<sub>2</sub>-enriched seedlings exhibited biomass values that were twice as large as those displayed by control seedlings grown in air of 350 ppm CO<sub>2</sub>. Likewise, Polley *et al.* (1999) reported that a doubling of the atmospheric CO<sub>2</sub> concentration for three months increased honey mesquite (*Prosopis glandulosa*) seedling root and shoot biomass by 37 and 46%, respectively.

Several studies have investigated the effects of elevated CO<sub>2</sub> on black locust (*Robinia pseudoacacia*) seedlings. Uselman *et al.* (2000), grew seedlings for three months at 700 ppm CO<sub>2</sub> and reported that this treatment increased the root exudation of organic carbon compounds by 20%, while Uselman *et al.* (1999) reported no CO<sub>2</sub>-induced increases in the root exudation of organic nitrogen compounds. Nonetheless, elevated CO<sub>2</sub> enhanced total seedling biomass by 14% (Uselman *et al.*, 2000).

In the study of Olesniewicz and Thomas (1999), black locust seedlings grown at twice-ambient CO<sub>2</sub> concentrations for two months exhibited a 69% increase in their average rate of nitrogen-fixation when they were not inoculated with an arbuscular mycorrhizal fungal species. It was further determined that the amount of seedling nitrogen derived from nitrogen-fixation increased in CO<sub>2</sub>-enriched plants by 212 and 90% in non-inoculated and inoculated seedlings, respectively. Ultimately, elevated CO<sub>2</sub> enhanced total plant biomass by 180 and 51% in non-inoculated and inoculated seedlings, respectively.

Thus, it would appear that as the CO<sub>2</sub> content of the air increases, nitrogen-fixing trees respond by exhibiting enhanced rates of photosynthesis and biomass production, as well as enhanced rates of nitrogen fixation.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/t/treesnitrofix.php>.

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#### 6.1.2.8. Oak

In this next section, we review several published responses of oak (genus *Quercus*) trees to atmospheric CO<sub>2</sub> enrichment.

In the two-month study of Anderson and Tomlinson (1998), northern red oak seedlings exposed to 700 ppm CO<sub>2</sub> displayed photosynthetic rates that were 34 and 69% greater than those displayed by control plants growing under well-watered and water-stressed conditions, respectively. Similarly, in the four-month study of Li *et al.* (2000), *Quercus myrtifolia* seedlings growing at twice-ambient CO<sub>2</sub> concentrations exhibited rates of photosynthesis at the onset of senescence that were 97% greater than those displayed by ambiently-growing seedlings.

Because elevated CO<sub>2</sub> enhances photosynthetic rates in oak trees, it should also lead to increased biomass production in them; and indeed it does. In the year-long study of Staudt *et al.* (2001), for example, *Quercus ilex* seedlings grown at 700 ppm CO<sub>2</sub> displayed trunk and branch biomasses that were 90% greater than those measured on seedlings growing at 350 ppm CO<sub>2</sub>. Also, in the eight-month inter-generational study performed by Polle *et al.* (2001), seedlings produced from acorns collected from ambient and CO<sub>2</sub>-enriched mother trees and germinated in air of either ambient or twice-ambient atmospheric CO<sub>2</sub> concentration displayed whole-plant biomass values that were 158 and 246% greater, respectively, than those exhibited by their respective control seedlings growing in ambient air.

In another study, Schulte *et al.* (1998) grew oak seedlings for 15 weeks at twice-ambient CO<sub>2</sub> concentrations, finding that elevated CO<sub>2</sub> enhanced seedling biomass by 92 and 128% under well-watered and water-stressed conditions, respectively; and in a similar study conducted by Tomlinson and Anderson (1998), water-stressed seedlings growing at 700 ppm CO<sub>2</sub> displayed biomass values that were similar to those exhibited by well-watered plants growing in ambient air. Thus, atmospheric CO<sub>2</sub> enrichment continues to benefit oak trees even under water-stressed conditions.

Additional studies have demonstrated that oak seedlings also respond positively to atmospheric CO<sub>2</sub> enrichment when they are faced with other environmental stresses and resource limitations. When pedunculate oak seedlings were subjected to two different soil nutrient

regimes, for example, Maillard *et al.* (2001) reported that a doubling of the atmospheric CO<sub>2</sub> concentration enhanced seedling biomass by 140 and 30% under high and low soil nitrogen conditions, respectively. And in the study of Usami *et al.* (2001), saplings of *Quercus myrsinaefolia* that were grown at 700 ppm CO<sub>2</sub> displayed biomass increases that were 110 and 140% greater than their ambiently-grown counterparts when they were simultaneously subjected to air temperatures that were 3 and 5°C greater than ambient temperature, respectively. Thus, elevated CO<sub>2</sub> concentrations tend to ameliorate some of the negative effects caused by growth-reducing stresses in oaks. In fact, when Schwanz and Polle (1998) reported that elevated CO<sub>2</sub> exposure caused reductions in the amounts of several foliar antioxidative enzymes in mature oak trees, they suggested that this phenomenon was the result of atmospheric CO<sub>2</sub> enrichment causing the trees to experience less oxidative stress and, therefore, that they had less need for antioxidative enzymes.

In some studies, elevated CO<sub>2</sub> has also been shown to reduce stomatal conductances in oak trees, thus contributing to greater tree water-use efficiencies. Tognetti *et al.* (1998a), for example, reported that oak seedlings growing near a natural CO<sub>2</sub>-emitting spring exhibited less water loss and more favorable turgor pressures than trees growing further away from the springs. In fact, the resulting improvement in water-use efficiency was so significant that Tognetti *et al.* (1998b) stated that "such marked increases in water-use efficiency under elevated CO<sub>2</sub> might be of great importance in Mediterranean environments in the perspective of global climate change."

In summary, it is clear that as the CO<sub>2</sub> content of the air increases, oak seedlings will likely display enhanced rates of photosynthesis and biomass production, regardless of air temperature, soil moisture, and soil nutrient status. Consequently, greater amounts of carbon will likely be removed from the atmosphere by the trees of this abundant genus and stored in their tissues and the soils in which they are rooted.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/t/treesoak.php>.

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### 6.1.2.9. Pine

#### 6.1.2.9.1. LOBLOLLY

Tissue *et al.* (1997) grew loblolly pine tree seedlings (*Pinus taeda* L.) for a period of four years in open-top chambers maintained at atmospheric CO<sub>2</sub> concentrations of either 350 or 650 ppm in a study of the long-term effects of elevated CO<sub>2</sub> on the growth of this abundant pine species. This experiment indicated there was a mean biomass accumulation in the seedlings grown in CO<sub>2</sub>-enriched air that was 90% greater than that attained by the seedlings grown in ambient air.

Johnson *et al.* (1998) reviewed eleven of their previously published papers, describing the results of a series of greenhouse and open-top chamber studies of the growth responses of loblolly pine seedlings to a range of atmospheric CO<sub>2</sub> and soil nitrogen concentrations. This work indicated that when soil nitrogen levels were so low as to be extremely deficient, or so high as to be toxic, growth responses to atmospheric CO<sub>2</sub> enrichment were negligible. For

moderate soil nitrogen deficiencies, however, a doubling of the air's CO<sub>2</sub> content sometimes boosted growth by as much as 1,000%. Consequently, since the nitrogen status of most of earth's ecosystems falls somewhere between extreme deficiency and toxicity, these results suggest that loblolly pine trees may experience large increases in growth as the air's CO<sub>2</sub> content continues to climb.

Naidu and DeLucia (1999) described the results of working one full year in 30-meter-diameter circular FACE plots maintained at atmospheric CO<sub>2</sub> concentrations of either 350 or 560 ppm in an originally 13-year-old loblolly pine plantation in North Carolina, USA, where they determined the effects of the elevated CO<sub>2</sub> treatment on the productivity of the trees, which were growing in soil that was characteristically low in nitrogen and phosphorus. After the first year of atmospheric CO<sub>2</sub> enrichment in this *Duke Forest Face Study*, the growth rate of the CO<sub>2</sub>-enriched trees was about 24% greater than that of the trees exposed to ambient CO<sub>2</sub>, in spite of the likelihood of soil nutrient limitations and a severe summer drought (rainfall in August 1997 was about 90% below the 50-year average).

After four years of work at the Duke Forest Face Site, Finzi *et al.* (2002) reported that the extra 200 or so ppm of CO<sub>2</sub> had increased the average yearly dry matter production of the CO<sub>2</sub>-enriched trees by 32%, while at the eight-year point of the experiment Moore *et al.* (2006) reported there had been a sustained increase in trunk basal area increment that varied between 13 and 27% with variations in weather and the timing of growth. What is more, they say "there was no evidence of a decline in the relative enhancement of tree growth by elevated CO<sub>2</sub> as might be expected if soil nutrients were becoming progressively more limiting," which many people had expected would occur in light of the site's low soil nitrogen and phosphorus content. In addition, at the six-year point of the study Pritchard *et al.* (2008) determined that the extra CO<sub>2</sub> had increased the average standing crop of fine roots by 23%.

Returning to other types of studies, Gavazzi *et al.* (2000) grew one-year-old loblolly pine seedlings for about four months in pots placed within growth chambers maintained at atmospheric CO<sub>2</sub> concentrations of either 360 or 660 ppm and adequate or inadequate levels of soil moisture, while the pots were seeded with a variety of C<sub>3</sub> and C<sub>4</sub> weeds. In the course of this experiment, they found that total seedling biomass was always greater under well-watered as opposed to water-stressed conditions, and that elevated CO<sub>2</sub> increased total seedling biomass by 22% in both water treatments. In the elevated CO<sub>2</sub> and water-stressed treatment, however, they also found that seedling root-to-shoot ratios were about 80% greater than they were in the elevated CO<sub>2</sub> and well-watered treatment, due to a 63% increase in root biomass. In the case of the weeds, total biomass was also always greater under well-watered compared to water-stressed conditions. However, the elevated CO<sub>2</sub> did *not* increase weed biomass; in fact, it *reduced* it by approximately 22%. Consequently, in assessing the effects of elevated CO<sub>2</sub> on competition between loblolly pine seedlings and weeds, the seedlings were definitely the winners, with the researchers concluding that the CO<sub>2</sub>-induced increase in root-to-shoot ratio under water-stressed conditions may "contribute to an improved ability of loblolly pine to compete against weeds on dry sites."

Working with data obtained from stands of loblolly pine plantations at 94 locations scattered throughout the southeastern United States, Westfall and Amateis (2003) employed mean height measurements made at three-year intervals over a period of 15 years to calculate a *site index* related to mean growth rate for each of the five three-year periods, which index would be expected to increase monotonically if growth rates were being enhanced above "normal" by some monotonically-increasing growth-promoting factor. This protocol indicated, in their words, that "mean site index over the 94 plots consistently increased at each remeasurement period," which would suggest, as they phrase it, that "loblolly pine plantations are realizing greater than expected growth rates," and, we would add, that the growth rate increases are growing larger and larger with each succeeding three-year period.

As for what might be causing the monotonically increasing growth rates of loblolly pine trees over the entire southeastern region of the United States, the two researchers say that in addition to rising atmospheric CO<sub>2</sub> concentrations, "two other likely factors that could affect growth are temperature and precipitation." However, they report that a review of annual precipitation amounts and mean ground surface temperatures showed no trends in these factors over the period of their study. They also suggest that if increased nitrogen deposition were the cause, "such a factor would have to be acting on a regional scale to produce growth increases over the range of study plots." Hence, they are partial to the *aerial fertilization effect of atmospheric CO<sub>2</sub> enrichment* explanation. What is more, they note that "similar results were reported by Boyer (2001) for natural stands of longleaf pine, where increases in dominant stand height are occurring over generations on the same site."

Could it be that the results of these comprehensive studies are manifestations of the *greening of the earth* phenomenon, which has been postulated by Idso (1982, 1986, 1995) to result from the historical increase in the air's CO<sub>2</sub> content? The many observations filed under the several sub-sections of the Greening of the Earth heading later in this chapter suggest that such may well be the case. Such is also suggested by the results of the studies reported here, which indicate that as the CO<sub>2</sub> content of the air continues to rise, loblolly pine trees will likely experience significant increases in biomass production, even on nutrient-poor soils, during times of drought, and in competition with weeds.

Additional information on this topic, including reviews loblolly pine trees not discussed here, can be found at [http://www.co2science.org/subject/t/subject\\_t.php](http://www.co2science.org/subject/t/subject_t.php), under the heading Trees, Types, Pine, Loblolly.

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#### 6.1.2.9.2. PONDEROSA

Walker *et al.* (1998b) grew Ponderosa pine seedlings (*Pinus ponderosa* Dougl. ex P. Laws & C. Laws) for an entire year in *controlled environment chambers* with atmospheric CO<sub>2</sub> concentrations of either 350 (ambient), 525 or 700 ppm. In addition, low or high levels of nitrogen and phosphorus were supplied to determine the main and interactive effects of atmospheric CO<sub>2</sub> enrichment and soil nutrition on seedling growth and fungal colonization of the seedlings' roots. After twelve months, they found that phosphorus supply had little impact on overall seedling growth, while high nitrogen increased nearly every parameter measured, including root, shoot and total biomass, as did atmospheric CO<sub>2</sub> enrichment. Averaged over all nitrogen and phosphate treatments, total root dry weights at 525 and 700 ppm CO<sub>2</sub> were 92

and 49% greater, respectively, than those observed at ambient CO<sub>2</sub>, while shoot dry weights were 83 and 26% greater. Consequently, seedlings grown at 525 and 700 ppm CO<sub>2</sub> had total dry weights that were 86 and 35% greater, respectively, than those measured at ambient CO<sub>2</sub>. In addition, elevated CO<sub>2</sub> increased the total number of ectomycorrhizal fungi on roots by 170% at 525 ppm CO<sub>2</sub> and 85% at 700 ppm CO<sub>2</sub> relative to the number observed at ambient CO<sub>2</sub>.

Walker *et al.* (1998a) grew Ponderosa pine seedlings for *two* growing seasons *out-of-doors in open-top chambers* having atmospheric CO<sub>2</sub> concentrations of 350, 525 and 700 ppm on soils of low, medium and high nitrogen content to determine the interactive effects of these variables on juvenile tree growth. The elevated CO<sub>2</sub> concentrations had little effect on most growth parameters after the first growing season, with the one exception of belowground biomass, which increased with both CO<sub>2</sub> and soil nitrogen. After two growing seasons, however, elevated CO<sub>2</sub> significantly increased all growth parameters, including tree height, stem diameter, shoot weight, stem volume and root volume, with the greatest responses typically occurring at the highest CO<sub>2</sub> concentration in the highest soil nitrogen treatment. Root volume at 700 ppm CO<sub>2</sub> and high soil nitrogen, for example, exceeded that of all other treatments by at least 45%, as did shoot volume by 42%. Similarly, at high CO<sub>2</sub> and soil nitrogen coarse root and shoot weights exceeded those at ambient CO<sub>2</sub> and high nitrogen by 80 and 88%, respectively.

Johnson *et al.* (1998) reviewed eleven of their previously published papers (including the two discussed above) in which they describe the results of a series of greenhouse and open-top chamber studies of the growth responses of Ponderosa pine seedlings to a range of atmospheric CO<sub>2</sub> and soil nitrogen concentrations. These studies indicated that when soil nitrogen levels were so low as to be extremely deficient, or so high as to be toxic, growth responses to atmospheric CO<sub>2</sub> enrichment were negligible. For moderate soil nitrogen deficiencies, however, a doubling of the air's CO<sub>2</sub> content sometimes boosted growth by as much as 1,000%. In addition, atmospheric CO<sub>2</sub> enrichment mitigated the negative growth response of ponderosa pine to extremely high soil nitrogen in two separate studies.

Maherali and DeLucia (2000) grew Ponderosa pine seedlings for six months in controlled environment chambers maintained at atmospheric CO<sub>2</sub> concentrations ranging from 350 to 1100 ppm, while they were subjected to either low (15/25°C night/day) or high (20/30°C night/day) temperatures. This study revealed that although elevated CO<sub>2</sub> had no significant effect on stomatal conductance, seedlings grown in the high temperature treatment exhibited a 15% increase in this parameter relative to seedlings grown in the low temperature treatment. Similarly, specific hydraulic conductivity, which is a measure of the amount of water moving through a plant relative to its leaf or needle area, also increased in the seedlings exposed to the high temperature treatment. In addition, biomass production rose by 42% in the low temperature treatment and 62% in the high temperature treatment when the atmospheric CO<sub>2</sub> concentration was raised from 350 to 1100 ppm.

Tingey *et al.* (2005) studied the effects of atmospheric CO<sub>2</sub> enrichment (to approximately 350 ppm above ambient) on the fine-root architecture of Ponderosa pine seedlings growing in open-top chambers via minirhizotron tubes over a period of four years. This experiment

showed that "elevated CO<sub>2</sub> increased both fine root extensity (degree of soil exploration) and intensity (extent that roots use explored areas) but had no effect on mycorrhizae," the latter of which observations was presumed to be due to the fact that soil nitrogen was not limiting to growth in this study. More specifically, they report that "extensity increased 1.5- to 2-fold in elevated CO<sub>2</sub> while intensity increased only 20% or less," noting that similar *extensity* results had been obtained over shorter periods of 4 months to 2 years by Arnone (1997), Berntson and Bazzaz (1998), DeLucia *et al.* (1997) and Runion *et al.* (1997), while similar *intensity* results had been obtained by Berntson (1994).

Last of all, Soule and Knapp (2006) studied Ponderosa pine trees growing naturally at eight different sites within the Pacific Northwest of the United States, in order to see how they may have responded to the increase in the atmosphere's CO<sub>2</sub> concentration that occurred after 1950. In selecting these sites, they chose locations that "fit several criteria designed to limit potential confounding influences associated with anthropogenic disturbance." They also say they selected locations with "a variety of climatic and topoedaphic conditions, ranging from extremely water-limiting environments ... to areas where soil moisture should be a limiting factor for growth only during extreme drought years," additionally noting that all sites were located in areas "where ozone concentrations and nitrogen deposition are typically low."

At each of the eight sites that met all of these criteria, Soule and Knapp obtained core samples from about 40 mature trees that included "the potentially oldest trees on each site," so that their results would indicate, as they put it, "the response of mature, naturally occurring ponderosa pine trees that germinated before anthropogenically elevated CO<sub>2</sub> levels, but where growth, particularly post-1950, has occurred under increasing and substantially higher atmospheric CO<sub>2</sub> concentrations." Utilizing meteorological evaluations of the Palmer Drought Severity Index, they thus compared ponderosa pine radial growth rates during matched wet and dry years pre- and post-1950.

So what did they find? Overall, the two researchers report finding a post-1950 radial growth enhancement that was "more pronounced during drought years compared with wet years, and the greatest response occurred at the most stressed site." As for the magnitude of the response, they determined that "the relative change in growth [was] upward at seven of our [eight] sites, ranging from 11 to 133%."

With respect to the meaning and significance of their observations, Soule and Knapp say their results "showing that radial growth has increased in the post-1950s period ... while climatic conditions have generally been unchanged, suggest that nonclimatic driving forces are operative." In addition, they say that "these radial growth responses are generally consistent with what has been shown in long-term open-top chamber (Idso and Kimball, 2001) and FACE studies (Ainsworth and Long, 2005)." Hence, they say their findings suggest that "elevated levels of atmospheric CO<sub>2</sub> are acting as a driving force for increased radial growth of ponderosa pine, but that the overall influence of this effect may be enhanced, reduced or obviated by site-specific conditions."



Summarizing their findings -- which illustrate what one would expect from the results of the growth chamber and field studies described above -- Soule and Knapp recount how they had "hypothesized that ponderosa pine...would respond to gradual increases in atmospheric CO<sub>2</sub> over the past 50 years, and that these effects would be most apparent during drought stress and on environmentally harsh sites," and they state in their very next sentence that their results "support these hypotheses." Hence, they conclude their paper by stating it is likely that "an atmospheric CO<sub>2</sub>-driven growth-enhancement effect exists for ponderosa pine growing under specific natural conditions within the [USA's] interior Pacific Northwest," providing yet another important real-world example of the ongoing CO<sub>2</sub>-induced *greening of the earth*.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/t/treesponderosa.php>.

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#### 6.1.2.9.3. SCOTS

Rouhier and Read (1998) grew Scots pine seedlings (*Pinus sylvestris* L.) for four months in growth cabinets maintained at atmospheric CO<sub>2</sub> concentrations of either 350 or 700 ppm. In addition, one third of the seedlings were inoculated with one species of mycorrhizal fungi, one third were inoculated with another species, and one third were not inoculated at all, in order to determine the effects of elevated CO<sub>2</sub> on mycorrhizal fungi and their interactive effects on seedling growth. These procedures resulted in the doubled atmospheric CO<sub>2</sub> content increasing seedling dry mass by an average of 45% regardless of fungal inoculation. In addition, the extra CO<sub>2</sub> increased the number of hyphal tips associated with seedling roots by about 62% for both fungal species. Hyphal growth was also accelerated by elevated CO<sub>2</sub>; and after 55 days of treatment, the mycorrhizal network produced by one of the fungal symbionts occupied 444% more area than its counterpart exposed to ambient CO<sub>2</sub>.

These results suggest that as the air's CO<sub>2</sub> content continues to rise, fungal symbionts of Scots pine will likely receive greater allocations of carbon from their host. This carbon can be used to increase their mycorrhizal networks, which would enable the fungi to explore greater volumes of soil in search of minerals and nutrients to benefit the growth of its host. In addition, by receiving greater allocations of carbon, fungal symbionts may keep photosynthetic down regulation from occurring, as they provide an additional sink for leaf-produced carbohydrates.

Janssens *et al.* (1998) grew three-year-old Scots pine seedlings in open-top chambers kept at ambient and 700 ppm atmospheric CO<sub>2</sub> concentrations for six months, while they studied the effects of elevated CO<sub>2</sub> on root growth and respiration. In doing so, they learned that the elevated CO<sub>2</sub> treatment significantly increased total root length by 122% and dry mass by 135% relative to the roots of seedlings grown in ambient-CO<sub>2</sub> air. In addition, although starch

accumulation in the CO<sub>2</sub>-enriched roots was nearly 90% greater than that observed in the roots produced in the ambient-CO<sub>2</sub> treatment, the carbon-to-nitrogen ratio of the CO<sub>2</sub>-enriched roots was significantly *lower* than that of the control-plant roots, indicative of the fact that they contained an even greater relative abundance of nitrogen. The most important implication of this study, therefore, was that Scots pine seedlings will likely be able to find the nitrogen they need to sustain large growth responses to atmospheric CO<sub>2</sub> enrichment with the huge root systems they typically produce in CO<sub>2</sub>-enriched air.

Kainulainen *et al.* (1998) constructed open-top chambers around Scots pine trees that were about twenty years old and fumigated them with combinations of ambient or CO<sub>2</sub>-enriched air (645 ppm) and ambient or twice-ambient (20 to 40 ppb) ozone-enriched air for three growing seasons to study the interactive effects of these gases on starch and secondary metabolite production. In doing so, they determined that elevated CO<sub>2</sub> and O<sub>3</sub> (ozone) had no significant impact on starch production in Scots pine, even after two years of treatment exposure. However, near the end of the third year, the elevated CO<sub>2</sub> alone significantly enhanced starch production in current-year needles, although neither extra CO<sub>2</sub>, extra O<sub>3</sub>, nor combinations thereof had any significant effects on the concentrations of secondary metabolites they investigated.

Kellomaki and Wang (1998) constructed *closed*-top chambers around 30-year-old Scots pine trees, which they fumigated with air containing either 350 or 700 ppm CO<sub>2</sub> at ambient and elevated (ambient plus 4°C) air temperatures for one full year, after which they assessed tree water-use by measuring cumulative sap flow for 32 additional days. This protocol revealed that the CO<sub>2</sub>-enriched air reduced cumulative sap flow by 14% at ambient air temperatures, but that sap flow was unaffected by atmospheric CO<sub>2</sub> concentration in the trees growing at the elevated air temperatures. These findings suggest that cumulative water-use by Scotts pine trees in a CO<sub>2</sub>-enriched world of the future will likely be less than or equal to -- but no more than -- what it is today.

Seven years later, however, Wang *et al.* (2005) published a report of a study in which they measured sap flow, crown structure and microclimatic parameters in order to calculate the transpiration rates of individual 30-year-old Scots pine trees that were maintained for a period of *three* years in ambient air and air enriched with an extra 350 ppm of CO<sub>2</sub> and/or warmed by 2 to 6°C in closed-top chambers constructed within a naturally-seeded stand of the trees. As they describe it, the results of this experiment indicated that "(i) elevated CO<sub>2</sub> significantly enhanced whole-tree transpiration rate during the first measuring year [by 14%] due to a large increase in whole-tree foliage area, 1998, but reduced it in the subsequent years of 1999 and 2000 [by 13% and 16%, respectively] as a consequence of a greater decrease in crown conductance which off-set the increase in foliage area per tree; (ii) trees growing in elevated temperature always had higher sap flow rates throughout three measuring years [by 54%, 45% and 57%, respectively]; and (iii) the response of sap flow to the combination of elevated temperature and CO<sub>2</sub> was similar to that of elevated temperature alone, indicating a dominant role for temperature and a lack of interaction between elevated CO<sub>2</sub> and temperature." These observations suggest that as the air's CO<sub>2</sub> content continues to rise, we probably can expect to

see a decrease in evaporative water loss rates from naturally-occurring stands of Scots pine trees ... unless there is a large concurrent increase in air temperature. As demonstrated in various places throughout our website, however, there is good reason to believe we will not see *CO<sub>2</sub>-induced* global temperature increases of the magnitude employed in this study during what yet remains of the current interglacial.

Also working with closed-top chambers that were constructed around 20-year-old Scots pines and fumigated with air containing 350 and 700 ppm CO<sub>2</sub> at ambient and elevated (ambient plus 4°C) air temperatures for a period of three years were Peltola *et al.* (2002), who studied the effects of elevated CO<sub>2</sub> and air temperature on stem growth in this coniferous species when it was growing on a soil low in nitrogen. After three years of treatment, they found that cumulative stem diameter growth in the CO<sub>2</sub>-enriched trees growing at ambient air temperatures was 57% greater than that displayed by control trees growing at ambient CO<sub>2</sub> and ambient air temperatures, while the trees exposed to elevated CO<sub>2</sub> and elevated air temperature exhibited cumulative stem-diameter growth that was 67% greater than that displayed by trees exposed to ambient-CO<sub>2</sub> air and ambient air temperatures. Consequently, as the air's CO<sub>2</sub> content continues to rise, Scots pine trees will likely respond by increasing stem-diameter growth, even if growing on soils low in nitrogen, and even if air temperatures rise by as much as 4°C.

In a somewhat different type of study, Kainulainen *et al.* (2003) collected needle litter beneath 22-year-old Scots pines that had been growing for the prior three years in open-top chambers that had been maintained at atmospheric CO<sub>2</sub> concentrations of 350 and 600 ppm in combination with ambient and elevated (approximately 1.4 x ambient) ozone concentrations to determine the impacts of these variables on the subsequent decomposition of senesced needles. This they did by enclosing the needles in litterbags and placing the bags within a native litter layer in a Scots pine forest, where decomposition rates were assessed by measuring accumulated litterbag mass loss over a period of 19 months. Interestingly, the three researchers found that exposure to elevated CO<sub>2</sub> during growth did *not* affect subsequent rates of needle decomposition, nor did elevated O<sub>3</sub> exposure affect decomposition, nor did exposure to elevated concentrations of the two gases together affect it.

Finally, Bergh *et al.* (2003) used a boreal version of the process-based BIOMASS simulation model to quantify the individual and combined effects of elevated air temperature (2 and 4°C above ambient) and CO<sub>2</sub> concentration (350 ppm above ambient) on the net primary production (NPP) of Scots pine forests growing in Denmark, Finland, Iceland, Norway and Sweden. This work revealed that air temperature increases of 2 and 4°C led to mean NPP increases of 11 and 20%, respectively. However, when the air's CO<sub>2</sub> concentration was simultaneously increased from 350 to 700 ppm, the corresponding mean NPP increases rose to 41 and 55%. Last of all, when the air's CO<sub>2</sub> content was doubled at the prevailing ambient temperature, the mean value of the NPP rose by 27%. Consequently, as the air's CO<sub>2</sub> content continues to rise, Ponderosa pines of Denmark, Finland, Iceland, Norway and Sweden should grow ever more productively; and if air temperature also rises, they will likely grow better still.

Given the above results, as the air's CO<sub>2</sub> content continues to rise, we can expect to see the root systems of Scots pines significantly enhanced, together with the mycorrhizal fungal networks that live in close association with them and help secure the nutrients the trees need to sustain large CO<sub>2</sub>-induced increases in biomass production. Concurrently, we can expect to see much smaller changes in total evaporative water loss, which means that whole-tree *water use efficiency* should also be significantly enhanced.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/t/treesscots.php>.

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#### 6.1.2.10. Spruce

In this next section, we review some recently published responses of spruce trees (genus *Picea*) to atmospheric CO<sub>2</sub> enrichment.

Several studies have recently documented the effects of elevated CO<sub>2</sub> on photosynthesis in various varieties of spruce. In the relatively short-term study of Tjoelker *et al.* (1998a), black spruce seedlings grown for three months at atmospheric CO<sub>2</sub> concentrations of 580 ppm exhibited photosynthetic rates that were about 28% greater than those displayed by control seedlings fumigated with air containing 370 ppm CO<sub>2</sub>. Similarly, Egli *et al.* (1998) reported that Norway spruce seedlings grown at 570 ppm CO<sub>2</sub> displayed photosynthetic rates that were 35% greater than those exhibited by seedlings grown at 370 ppm. In two branch bag studies conducted on mature trees, it was demonstrated that twice-ambient levels of atmospheric CO<sub>2</sub> enhanced rates of photosynthesis in current-year needles by 50% in Norway spruce (Roberntz and Stockfors, 1998) and 100% in Sitka spruce (Barton and Jarvis, 1999). Finally, in the four-year open-top chamber study of Murray *et al.* (2000), the authors reported that Sitka spruce seedlings growing at 700 ppm CO<sub>2</sub> exhibited photosynthetic rates that were 19 and 33% greater than those observed in control trees growing in ambient air and receiving low and high amounts of nitrogen fertilization, respectively.

Because elevated CO<sub>2</sub> enhances photosynthetic rates in spruce species, this phenomenon should lead to increased biomass production in these important coniferous trees; and so it does. In the short-term three-month study of Tjoelker *et al.* (1998b), for example, black spruce seedlings receiving an extra 210 ppm CO<sub>2</sub> displayed final dry weights that were about 20% greater than those of seedlings growing at ambient CO<sub>2</sub>. Similarly, after growing Sitka spruce for three years in open-top chambers, Centritto *et al.* (1999) reported that a doubling of the atmospheric CO<sub>2</sub> concentration enhanced sapling dry mass by 42%.

In summary, it is clear that as the CO<sub>2</sub> content of the air increases, spruce trees will likely display enhanced rates of photosynthesis and biomass production, regardless of soil nutrient status. Consequently, rates of carbon sequestration by this abundant coniferous forest species will likely be enhanced.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/t/treespruce.php>.

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#### 6.1.2.11. Tropical

Several studies have recently documented the effects of elevated atmospheric CO<sub>2</sub> concentrations on photosynthesis in various tropical and sub-tropical trees. In the relatively short-term study of Lovelock *et al.* (1999a), for example, seedlings of the tropical tree *Copaifera aromatica* that were grown for two months at an atmospheric CO<sub>2</sub> concentration of 860 ppm exhibited photosynthetic rates that were consistently 50-100% greater than those displayed by control seedlings fumigated with air containing 390 ppm CO<sub>2</sub>. Similarly, Lovelock *et al.* (1999b) reported that a 10-month 390-ppm increase in the air's CO<sub>2</sub> content boosted rates of net photosynthesis in 30-m tall *Luehea seemannii* trees by 30%. Likewise, in the review paper of Schaffer *et al.* (1999), it was noted that atmospheric CO<sub>2</sub> enrichment had previously been shown to enhance rates of net photosynthesis in a number of tropical and sub-tropical fruit trees, including avocado, banana, citrus, mango and mangosteen. Even at the ecosystem level, Lin *et al.* (1998) found that a 1700-m<sup>2</sup> synthetic rainforest mesocosm displayed a 79% enhancement in net ecosystem carbon exchange rate in response to a 72% increase in the air's CO<sub>2</sub> content.

Because elevated CO<sub>2</sub> enhances photosynthetic rates in tropical and sub-tropical trees, it should also lead to increased carbohydrate and biomass production in these species. And it does! At a tropical forest research site in Panama, for example, twice-ambient CO<sub>2</sub> concentrations enhanced foliar sugar concentrations by up to 30% (Wurth *et al.*, 1998), while doubling the foliar concentrations of starch (Lovelock *et al.*, 1998) in a number of tree species. Also, in the study of Hoffmann *et al.* (2000), elevated CO<sub>2</sub> (700 ppm) enhanced dry weights of an "uncut" Brazilian savannah tree species (*Keilmeyera coriacea*) by about 50%, while it enhanced the dry weight of the same "cut" species by nearly 300%. Although not specifically

quantified, Schaffer *et al.* (1997) noted that twice-ambient CO<sub>2</sub> exposure for one year obviously enhanced dry mass production in two mango ecotypes. Finally, in the six-month study of Sheu *et al.* (1999), a doubling of the atmospheric CO<sub>2</sub> concentration increased seedling dry weight in *Schima superba* by 14 and 49% when grown at ambient and elevated (5°C above ambient) air temperatures, respectively.

Thus, it is clear that as the air's CO<sub>2</sub> content rises, tropical and sub-tropical trees will likely display enhanced rates of photosynthesis and biomass production, even under conditions of herbivory and elevated air temperature. Consequently, greater carbon sequestration will also likely occur within earth's tropical and sub-tropical forests as ever more CO<sub>2</sub> accumulates in the atmosphere.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/t/treestropical.php>.

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#### 6.1.2.12. Wood Density

Numerous experiments have demonstrated that trees grown in air enriched with CO<sub>2</sub> nearly always sequester more biomass in their trunks and branches than do trees grown in ambient air. Several studies have also looked at the effects of elevated CO<sub>2</sub> on the *density* of that sequestered biomass, some of which are summarized here.

Rogers *et al.* (1983) observed no difference in the wood density of loblolly pine (*Pinus taeda*) trees grown at 340 and 718 ppm CO<sub>2</sub> for ten weeks; but they found a 33% CO<sub>2</sub>-induced increase in the wood density of sweetgum (*Liquidambar styraciflua*) trees that were grown at these concentrations for only eight weeks. Doyle (1987) and Telewski and Strain (1987) studied the same two tree species over three growing seasons in air of 350 and 650 ppm CO<sub>2</sub>, finding no effect of atmospheric CO<sub>2</sub> enrichment on the stem density of sweetgum, but a mean increase of 9% in the stem density of loblolly pine.

Conroy *et al.* (1990) grew seedlings of two *Pinus radiata* families at 340 and 660 ppm CO<sub>2</sub> for 114 weeks, finding CO<sub>2</sub>-induced trunk density increases for the two families of 5.4 and 5.6% when soil phosphorus was less than adequate and increases of 5.6 and 1.2% when it was non-limiting. In a similar study, Hattenschwiler *et al.* (1996) grew six genotypes of clonally-propagated four-year-old Norway spruce (*Picea abies*) for three years at CO<sub>2</sub> concentrations of 280, 420 and 560 ppm at three different rates of wet nitrogen deposition. On average, they found that wood density was 12% greater in the trees grown at the two higher CO<sub>2</sub> concentrations than it was in the trees grown at 280 ppm.

Norby *et al.* (1996) grew yellow poplar or "tulip" trees (*Liriodendron tulipifera*) at ambient and ambient plus 300 ppm CO<sub>2</sub> for three years, during which time the wood density of the trees increased by approximately 7%. Tognetti *et al.* (1998) studied two species of oak tree - one deciduous (*Quercus pubescens*) and one evergreen (*Quercus ilex*) - growing in the vicinity of CO<sub>2</sub> springs in central Italy that raised the CO<sub>2</sub> concentration of the surrounding air by approximately 385 ppm. This increase in the air's CO<sub>2</sub> content increased the wood density of the deciduous oaks by 4.2% and that of the evergreen oaks by 6.4%.

Telewski *et al.* (1999) grew loblolly pine trees for four years at ambient and ambient plus 300 ppm CO<sub>2</sub>. In their study, wood density determined directly from mass and volume measurements was increased by 15% by the extra CO<sub>2</sub>; while average ring density determined by X-ray densitometry was increased by 4.5%.

Beismann *et al.* (2002) grew different genotypes of spruce and beech (*Fagus sylvatica*) seedlings for four years in open-top chambers maintained at atmospheric CO<sub>2</sub> concentrations of 370 and 590 ppm in combination with low and high levels of wet nitrogen application on both rich calcareous and poor acidic soils to study the effects of these factors on seedling toughness (fracture characteristics) and rigidity (bending characteristics such as modulus of elasticity). They found that some genotypes of each species were sensitive to elevated CO<sub>2</sub>, while others were not. Similarly, some were responsive to elevated nitrogen deposition, while others were not. Moreover, such responses were often dependent upon soil type. Averaged across all tested genotypes, however, atmospheric CO<sub>2</sub> enrichment increased wood toughness in spruce seedlings grown on acidic soils by 12 and 18% at low and high levels of nitrogen deposition, respectively. In addition, atmospheric CO<sub>2</sub> enrichment increased this same wood property in spruce seedlings grown on calcareous soils by about 17 and 14% with low and high levels of nitrogen deposition, respectively. In contrast, elevated CO<sub>2</sub> had no significant effects on the mechanical wood properties of beech seedlings, regardless of soil type.

Finally, Kilpelainen *et al.* (2003) erected 16 open-top chambers within a 15-year-old stand of Scots pines growing on a nutrient-poor sandy soil of low nitrogen content near the Mekrijarvi Research Station of the University of Joensuu, Finland. Over the next three years they maintained the trees within these chambers in a well-watered condition, while they enriched the air in half of the chambers to a mean daytime CO<sub>2</sub> concentration of approximately 580 ppm and maintained the air in half of each of the two CO<sub>2</sub> treatments at 2°C above ambient. In the ambient temperature treatment the 60% increase in the air's CO<sub>2</sub> concentration significantly increased latewood density by 27% and maximum wood density by 11%, while in the elevated-temperature treatment it significantly increased latewood density by 25% and maximum wood density by 15%. These changes led to mean overall CO<sub>2</sub>-induced wood density increases of 2.8% in the ambient-temperature treatment and 5.6% in the elevated-temperature treatment.

In light of these several observations, it is clear that different species of trees sometimes respond differently to atmospheric CO<sub>2</sub> enrichment, and that they respond with still greater variety under different sets of environmental conditions. In general, however, atmospheric CO<sub>2</sub> enrichment tends to increase wood density in both seedlings and mature trees more often than not, thereby also increasing a number of strength properties of their branches and trunks.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/w/wooddensity.php>.

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#### 6.1.2.13. Forests

Forests contain perennial trees that remove CO<sub>2</sub> from the atmosphere during photosynthesis and store it's carbon within their woody tissues for decades to periods sometimes in excess of a thousand years. Thus, it is important to understand how increases in the air's CO<sub>2</sub> content affect forest productivity and carbon sequestration, which has a great impact on the rate of rise of the air's CO<sub>2</sub> concentration. In this summary, we review several recent scientific publications pertaining to these subjects.

By examining various properties of tree rings, researchers can deduce how historical increases in the air's CO<sub>2</sub> concentration have already affected tree productivity and water use efficiency.

Duquesnay *et al.* (1998), for example, analyzed the relative amounts of  $^{12}\text{C}$  and  $^{13}\text{C}$  present in yearly growth rings of beech trees raised in silviculture regimes in northeastern France, determining that their intrinsic water use efficiencies rose by approximately 33% during the past century, as the air's  $\text{CO}_2$  concentration rose from approximately 280 to 360 ppm. In another case, Rathgeber *et al.* (2000) used tree-ring density data to create an historical productivity baseline for forest stands of *Pinus halepensis* in southeastern France, from which they determined that the net productivity of such forests would increase by 8 to 55% with a doubling of the air's  $\text{CO}_2$  content. Finally, when running a forest growth model based on empirical observations reported in the literature, Lloyd (1999) determined that the rise in the atmospheric  $\text{CO}_2$  concentration since the onset of the Industrial Revolution likely increased the net primary productivity of mature temperate deciduous forests by about 7%. In addition, he determined that a proportional increase in anthropogenic nitrogen deposition likely increased forest net primary productivity by 25%. And when he combined the two effects, the net primary productivity stimulation rose to 40%, which is more than the sum of the individual growth enhancements resulting from the increases in  $\text{CO}_2$  and nitrogen.

The results of these studies demonstrate that historic increases in the air's  $\text{CO}_2$  content have already conferred great benefits upon earth's forests. But will future increases in the air's  $\text{CO}_2$  concentration continue to do so? Several research teams have embarked on long-term studies of various forest communities in an attempt to address this important question. What follows are some important observations that have been made from their mostly-ongoing  $\text{CO}_2$ -enrichment studies.

Back in 1996, circular FACE plots (30-m diameter) receiving atmospheric  $\text{CO}_2$  concentrations of 360 and 560 ppm were established in a 15-year-old loblolly pine (*Pinus taeda*) plantation in North Carolina, USA, to study the effects of elevated  $\text{CO}_2$  on the growth and productivity of this particular forest community, which also had several hardwood species present in the understory beneath the primary coniferous canopy. Using this experimental set-up as a platform for several experiments, Hymus *et al.* (1999) reported that net photosynthetic rates of  $\text{CO}_2$ -enriched loblolly pine trees were 65% greater than rates observed in control trees exposed to ambient air. These greater rates of carbon fixation contributed to the 24% greater growth rates observed in the  $\text{CO}_2$ -enriched pine trees in the first year of this long-term study (Naidu and DeLucia 1999). In addition, DeLucia and Thomas (2000) reported that the elevated  $\text{CO}_2$  increased rates of net photosynthesis by 50 to 160% in four subdominant hardwood species present in the forest understory. Moreover, for one species - sweetgum (*Liquidambar styraciflua*) - the extra  $\text{CO}_2$  enhanced rates of net photosynthesis in sun and shade leaves by 166 and 68%, respectively, even when the trees were naturally subjected to summer seasonal stresses imposed by high temperature and low soil water availability. Consequently, after two years of atmospheric  $\text{CO}_2$  enrichment, total ecosystem net primary productivity in the  $\text{CO}_2$ -enriched plots was 25% greater than that measured in control plots fumigated with ambient air.

In a similar large-scale study, circular (25-m diameter) FACE plots receiving atmospheric  $\text{CO}_2$  concentrations of 400 and 530 ppm were constructed within a ten-year-old sweetgum plantation in Tennessee, USA, to study the effects of elevated  $\text{CO}_2$  on the growth and

productivity of this forest community. After two years of treatment, Norby *et al.* (2001) reported that the modest 35% increase in the air's CO<sub>2</sub> content boosted tree biomass production by an average of 24%. In addition, Wullschlegler and Norby (2001) noted that CO<sub>2</sub>-enriched trees displayed rates of transpirational water loss that were approximately 10% lower than those exhibited by control trees grown in ambient air. Consequently, elevated CO<sub>2</sub> enhanced seasonal water use efficiencies of these mature sweetgum trees by 28 to 35%.

On a smaller scale, Pritchard *et al.* (2001) constructed idealized ecosystems (containing five different species) representative of regenerating longleaf pine (*Pinus palustris* Mill.) communities of the southeastern USA, fumigating them for 18 months with air containing 365 and 720 ppm CO<sub>2</sub> to study the effects of elevated CO<sub>2</sub> on this forest community. They reported that elevated CO<sub>2</sub> increased the above- and belowground biomass of the dominant longleaf pine individuals by 20 and 62%, respectively. At the ecosystem level, elevated CO<sub>2</sub> stimulated total aboveground biomass production by an average of 35%. Similar results for regenerating temperate forest communities have been reported by Berntson and Bazzaz (1998), who documented a 31% increase in Transition Hardwood-White Pine-Hemlock forest mesocosm biomass in response to two years of fumigation with twice-ambient concentrations of atmospheric CO<sub>2</sub>.

It is thus clear that as the air's CO<sub>2</sub> concentration continues to rise, forests will likely respond by exhibiting significant increases in total primary productivity and biomass production. Consequently, forests will likely grow much more robustly and significantly expand their ranges, as has already been documented in many parts of the world, including gallery forest in Kansas, USA (Knight *et al.*, 1994), and the Budal and Sjodal valleys in Norway (Olsson *et al.*, 2000). Such CO<sub>2</sub>-induced increases in growth and range expansion should ultimately result in large increases in global carbon sequestration within forests, and may actually reduce the rate of rise of the air's CO<sub>2</sub> concentration.

Additional information on this topic, including reviews on forests not discussed here, can be found at [http://www.co2science.org/subject/f/subject\\_f.php](http://www.co2science.org/subject/f/subject_f.php) under the heading Forests.

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### 6.1.3. Aquatic plants

As demonstrated above, it is universally acknowledged that atmospheric CO<sub>2</sub> enrichment typically enhances the growth and productivity of nearly all terrestrial plants. But what about *aquatic* plants? In this section we seek to answer that question.

#### 6.1.3.1. Freshwater Algae

How do freshwater algae respond to increases in the air's CO<sub>2</sub> content? The subject has not been thoroughly researched, but the results of the studies discussed below provide a glimpse of what the future may hold as the atmosphere's CO<sub>2</sub> concentration continues its upward course.

Working with cells of the freshwater alga *Chlorella pyrenoidosa*, Xia and Gao (2003) cultured them in Bristol's solution within controlled environment chambers maintained at low and high light levels (50 and 200  $\mu\text{mol}/\text{m}^2/\text{s}$ ) during 12-hour light periods that were followed by 12-hour dark periods for a total of 13 days, while the solutions in which the cells grew were continuously aerated with air of either 350 or 700 ppm CO<sub>2</sub>. When the cells were harvested (in the exponential growth phase) at the conclusion of this period, the biomass (cell density) of the twice-ambient CO<sub>2</sub> treatment was found to be 10.9% and 8.3% greater than that of the ambient-air treatment in the low- and high-light regimes, respectively, although only the high-light result was statistically significant. The two scientists thus concluded from these observations that a "doubled atmospheric CO<sub>2</sub> concentration would affect the growth of *C. pyrenoidosa* when it grows under bright solar radiation, and such an effect would increase by a great extent when the cell density becomes high." Their data also suggest that the same may well be true when the alga grows under *not-so-bright* conditions.

Working on a much larger scale "in the field" with six 1.5-m-diameter flexible plastic cylinders placed in the littoral zone of Lake Hampen in central Jutland, Denmark (three maintained at the ambient CO<sub>2</sub> concentration of the air and three enriched to ten times the ambient CO<sub>2</sub> concentration), Andersen and Andersen (2006) measured the CO<sub>2</sub>-induced growth response of a mixture of several species of filamentous freshwater algae dominated by *Zygnema* species, but containing some *Mougeotia* and *Spirogyra*. After one full growing season (May to November), they determined that the biomass of the microalgal mixture in the CO<sub>2</sub>-enriched cylinders was increased by 220% in early July, by 90% in mid-August, and by a whopping 3,750% in mid-November.

In another study of the subject, Schippers *et al.* (2004a) say "it is usually thought that unlike terrestrial plants, phytoplankton will not show a significant response to an increase of atmospheric CO<sub>2</sub>," but they note, in this regard, that "most analyses have not examined the full dynamic interaction between phytoplankton production and assimilation, carbon-chemistry and the air-water flux of CO<sub>2</sub>," and that "the effect of photosynthesis on pH and the dissociation of carbon (C) species have been neglected in most studies."

In an attempt to rectify this situation, Schippers *et al.* developed "an integrated model of phytoplankton growth, air-water exchange and C chemistry to analyze the potential increase of

phytoplankton productivity due to an atmospheric CO<sub>2</sub> elevation," and as a test of their model, they let the freshwater alga *Chlamydomonas reinhardtii* grow in 300-ml bottles filled with 150 ml of a nutrient-rich medium at enclosed atmospheric CO<sub>2</sub> concentrations of 350 and 700 ppm that they maintained at two air-water exchange rates characterized by CO<sub>2</sub> exchange coefficients of 2.1 and 5.1 m day<sup>-1</sup>, as described by Shippers *et al.* (2004b), while periodically measuring the biovolume of the solutions by means of an electronic particle counter. The results of this effort, as they describe it, "confirm the theoretical prediction that if algal effects on C chemistry are strong, increased phytoplankton productivity because of atmospheric CO<sub>2</sub> elevation should become proportional to the increased atmospheric CO<sub>2</sub>," which suggests that algal productivity "would double at the predicted increase of atmospheric CO<sub>2</sub> to 700 ppm." Although they note that "strong algal effects (resulting in high pH levels) at which this occurs are rare under natural conditions," they still predict that effects on algal production in freshwater systems could be such that a "doubling of atmospheric CO<sub>2</sub> may result in an increase of the productivity of more than 50%."

In the last of the few papers we have reviewed in this area, Logothetis *et al.* (2004) note that "the function and structure of the photosynthetic apparatus of many algal species resembles that of higher plants (Plumley and Smidt, 1984; Brown, 1988; Plumley *et al.*, 1993)," and that "unicellular green algae demonstrate responses to increased CO<sub>2</sub> similar to those of higher plants in terms of biomass increases (Muller *et al.*, 1993)." However, they also note that "little is known about the changes to their photosynthetic apparatus during exposure to high CO<sub>2</sub>," which deficiency they began to correct via a new experiment, wherein batches of the unicellular green alga *Scenedesmus obliquus* (wild type strain D3) were grown autotrophically in liquid culture medium for several days in a temperature-controlled water bath of 30°C at low (55 μmol m<sup>-2</sup> s<sup>-1</sup>) and high (235 μmol m<sup>-2</sup> s<sup>-1</sup>) light intensity while they were continuously aerated with air of either 300 or 100,000 ppm CO<sub>2</sub>. This protocol revealed that exposure to the latter high CO<sub>2</sub> concentration produces, in their words, a "reorganization of the photosynthetic apparatus" that "leads to enhanced photosynthetic rates, which ... leads to an immense increase of biomass." After five days under low light conditions, for example, the CO<sub>2</sub>-induced increase in biomass was approximately 300%, while under high light conditions it was approximately 600%.

Based on these few observations, it is not possible to draw any sweeping conclusions about the subject. However, they do indicate there may be a real potential for the ongoing rise in the air's CO<sub>2</sub> content to significantly stimulate the productivity of this freshwater contingent of earth's plants.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/a/aquaticplants.php>.

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#### 6.1.3.2. Freshwater Macrophytes

In this section we discuss the findings of papers that investigate the influence of CO<sub>2</sub> concentrations as it applies to *submersed*, *floating* and *emergent* freshwater macrophytes, beginning with studies of aquatic plants that live their lives *totally submersed* in freshwater environments.

For several multi-week periods, Idso (1997) grew specimens of corkscrew vallisneria (*Vallisneria spiralis*) in several 10- and 29-gallon glass tanks (containing 10-cm bottom-layers of common aquarium gravel) that were filled with tap water maintained within 0.5°C of either 18.2°C or 24.5°C, while the semi-sealed air spaces above these "Poor Man's Biospheres," as he christened them, were maintained at a number of different CO<sub>2</sub> concentrations. With the harvesting of plants at the end of the study, this protocol revealed that the CO<sub>2</sub>-induced growth enhancement of the plants was *linear* (in contrast to the gradually-declining CO<sub>2</sub>-induced growth enhancements typically exhibited by most terrestrial plants as the air's CO<sub>2</sub> content climbs ever higher), and that the linear relationship extended to the highest atmospheric CO<sub>2</sub> concentration studied: 2100 ppm. In addition, he found that the CO<sub>2</sub>-induced growth increase experienced by the plants in the higher of the two water temperature treatments (a 128% increase in going from an atmospheric CO<sub>2</sub> concentration of 365 ppm to one of 2100 ppm) was

3.5 times greater than that of the plants in the lower water temperature treatment. Although this response may seem rather dramatic, it is not unique; for Idso reports that Titus *et al.* (1990), who studied the closely related *Vallisneria americana*, "observed that the biomass of their experimental plants also rose linearly with the CO<sub>2</sub> content of the air above the water within which they grew, and that [it] did so from the value of the [then] current global mean (365 ppm) to a concentration fully *ten times larger* [our italics]."

In another study of a closely allied species, Yan *et al.* (2006) collected turions of *Vallisneria spirulosa* from Liangzi Lake, Hubei Province, China, and planted them in tanks containing 15-cm-deep layers of fertile lake sediments, topped with 40 cm of lake water, that were placed in two glasshouses - one maintained at the ambient atmospheric CO<sub>2</sub> concentration of 390 ppm and the other maintained at an elevated concentration of 1000 ppm - where the plants grew for a period of 120 days, after which they were harvested and the dry weights of their various organs determined. As they describe it, this work indicated that the "total biomass accumulation of plants grown in the elevated CO<sub>2</sub> was 2.3 times that of plants grown in ambient CO<sub>2</sub>, with biomass of leaves, roots and rhizomes increasing by 106%, 183% and 67%, respectively." Most spectacularly of all, they report that "turion biomass increased 4.5-fold," because "the mean turion numbers per ramet and mean biomass per turion in elevated CO<sub>2</sub> were 1.7-4.3 and 1.9-3.4 times those in ambient CO<sub>2</sub>."

Over in Denmark, in a study of small slow-growing evergreen perennials called *isoetids* that live submersed along the shores of numerous freshwater lakes, Andersen *et al.* (2006) grew specimens of *Littorella uniflora* in sediment cores removed from Lake Hampen in 75-liter tanks with 10-cm overburdens of filtered lake water for a period of 53 days, while measuring various plant, water and sediment properties, after which they destructively harvested the plants and measured their biomass. Throughout this period, half of the tanks had ambient air bubbled through their waters, while the other half were similarly exposed to a mixture of ambient air and pure CO<sub>2</sub> that produced a 10-fold increase in the air's CO<sub>2</sub> concentration. This ultra-CO<sub>2</sub>-enrichment led to a 30% increase in plant biomass, as well as "higher O<sub>2</sub> release to the sediment which is important for the cycling and retention of nutrients in sediments of oligotrophic softwater lakes." And when the ultra-CO<sub>2</sub>-enrichment was maintained for an entire growing season (May-November), Andersen and Andersen (2006) report that the ten-fold increase in aquatic CO<sub>2</sub> concentration enhanced the biomass production of *Littorella uniflora* by a much larger 78%.

In a study of an "in-between" type of plant that has *submersed* roots and rhizomes that are anchored in water-body sediments, but which has *floating* leaves on the surface of the water and *emergent* flowers that protrude above the water surface, Idso *et al.* (1990) grew water lilies (*Nymphaea marliac*) for two consecutive years in sunken metal stock tanks located out-of-doors at Phoenix, Arizona (USA) and enclosed within clear-plastic-wall open-top chambers through which air of either 350 or 650 ppm CO<sub>2</sub> was continuously circulated. This work revealed that in addition to the leaves of the plants being larger in the CO<sub>2</sub>-enriched treatment, there were 75% more of them than there were in the ambient-air tanks at the conclusion of the initial five-month-long growing season. Each of the plants in the high-CO<sub>2</sub> tanks also produced twice

as many flowers as the plants growing in ambient air; and the flowers that blossomed in the CO<sub>2</sub>-enriched air were more substantial than those that bloomed in the air of ambient CO<sub>2</sub> concentration: they had more petals, the petals were longer, and they had a greater percent dry matter content, such that each flower consequently weighed about 50% more than each flower in the ambient-air treatment. In addition, the stems that supported the flowers were slightly longer in the CO<sub>2</sub>-enriched tanks; and the percent dry matter contents of both the flower and leaf stems were greater, so that the total dry matter in the flower and leaf stems in the CO<sub>2</sub>-enriched tanks exceeded that of the flower and leaf stems in the ambient-air tanks by approximately 60%.

Just above the surface of the soil that covered the bottoms of the tanks, there were also noticeable differences. Plants in the CO<sub>2</sub>-enriched tanks had more and bigger basal rosette leaves, which were attached to longer stems of greater percent dry matter content, which led to the total biomass of these portions of the plants being 2.9 times greater than the total biomass of the corresponding portions of the plants in the ambient-air tanks. In addition, plants in the CO<sub>2</sub>-enriched tanks had more than twice as many unopened basal rosette leaves.

The greatest differences of all, however, were hidden within the soil that covered the bottoms of the stock tanks. When half of the plants were harvested at the conclusion of the first growing season, for example, the number of new rhizomes produced over that period was discovered to be 2.4 times greater in the CO<sub>2</sub>-enriched tanks than it was in the ambient-air tanks; while the number of major roots produced there was found to be 3.2 times greater. And as with all other plant parts, the percent dry matter contents of the new roots and rhizomes were also greater in the CO<sub>2</sub>-enriched tanks. Overall, therefore, the total dry matter production within the submerged soils of the water lily ecosystems was 4.3 times greater in the CO<sub>2</sub>-enriched tanks than it was in the ambient-air tanks; while the total dry matter production of all plant parts - those in the submerged soil, those in the free water, and those in the air above - was 3.7 times greater in the high-CO<sub>2</sub> enclosures.

Over the second growing season, the growth enhancement in the high-CO<sub>2</sub> tanks was somewhat less; but the plants in those tanks were so far ahead of the plants in the ambient-air tanks that in their first five months of growth, they produced what it took the plants in the ambient-air tanks fully 21 months to produce.

Moving on to plants that are exclusively *floating* freshwater macrophytes, Idso (1997) grew many batches of the common water fern (*Azolla pinnata*) over a wide range of atmospheric CO<sub>2</sub> concentrations at two different water temperatures (18.2°C and 24.5°C) in Poor Man's Biospheres for periods of several weeks. This work revealed that a 900-ppm increase in the CO<sub>2</sub> concentration of the air above the tanks led to only a 19% increase in the biomass production of the plants floating in the cooler water, but that it led to a 66% biomass increase in the plants floating in the warmer water.

In an earlier study of *Azolla pinnata*, Idso *et al.* (1989) conducted three separate two- to three-month experiments wherein they grew batches of the floating fern out-of-doors in adequately-

fertilized water contained in sunken metal stock tanks located within clear-plastic-wall open-top chambers that were continuously maintained at atmospheric CO<sub>2</sub> concentrations of either 340 or 640 ppm, during which time the plants were briefly removed from the water and weighed at weekly intervals, while their photosynthetic rates were measured at hourly intervals from dawn to dusk on selected cloudless days. As a result of this protocol, they found that the photosynthetic and growth rates of the plants growing in ambient air "first decreased, then stagnated, and finally became negative when mean air temperature rose above 30°C." In the high CO<sub>2</sub> treatment, on the other hand, they found that "the debilitating effects of high temperatures were reduced: in one case to a much less severe negative growth rate, in another case to merely a short period of zero growth rate, and in a third case to no discernible ill effects whatsoever - in spite of the fact that the ambient treatment plants in this instance all died."

Last of all, in a study of an *emergent* freshwater macrophyte, Ojala *et al.* (2002) grew water horsetail (*Equisetum fluviatile*) plants at ambient and double-ambient atmospheric CO<sub>2</sub> concentrations and ambient and ambient + 3°C air temperatures for three years, although the plants were only subjected to the double-ambient CO<sub>2</sub> condition for approximately five months of each year. This work revealed that the increase in air temperature boosted maximum shoot biomass by 60%, but that the elevated CO<sub>2</sub> had no effect on this aspect of plant growth. However, elevated CO<sub>2</sub> and temperature - both singly and in combination - positively impacted *root* growth, which was enhanced by 10, 15 and 25% by elevated air temperature, CO<sub>2</sub>, and the two factors together, respectively.

In light of the several experimental findings discussed above, we conclude that the ongoing rise in the air's CO<sub>2</sub> content will likely have significant positive impacts on most freshwater macrophytes, including submersed, floating and emergent species.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/a/aquaticmacrophytes.php>.

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### 6.1.3.3. Marine Macroalgae

How do marine macroalgae respond to increases in the air's CO<sub>2</sub> content? The results of the studies discussed below provide a glimpse of what the future may hold in this regard, as the atmosphere's CO<sub>2</sub> concentration continues its upward climb.

Gao *et al.* (1993) grew cultures of the red macroalgae *Gracilaria* sp. and *G. chilensis* in vessels enriched with nitrogen and phosphorus that were continuously aerated with normal air containing 350 ppm CO<sub>2</sub>, air enriched with an extra 650 ppm CO<sub>2</sub>, and air enriched with an extra 1250 ppm CO<sub>2</sub> for a period of 19 days. Compared to the control treatments, the relative growth enhancements in the + 650-ppm and +1250-ppm CO<sub>2</sub> treatments were 20% and 60%, respectively, for *G. chilensis*, and 130% and 190%, respectively, for the *Gracilaria* sp.

With respect to these findings, the researchers comment that "in their natural habitats, photosynthesis and growth of *Gracilaria* species are likely to be CO<sub>2</sub>-limited, especially when the population density is high and water movement is slow." Hence, as the air's CO<sub>2</sub> content continues to rise, these marine macroalgae should grow ever better in the years ahead. Such should also be the case with many other macroalgae, for Gao *et al.* note that "photosynthesis by most macroalgae is probably limited by inorganic carbon sources in natural seawater," citing the studies of Surif and Raven (1989), Maberly (1990), Gao *et al.* (1991) and Levavasseur *et al.* (1991) as evidence for this statement.

In a subsequent study, Kubler *et al.* (1999) grew *Lomentaria articulata*, a red seaweed common to the Northeast Atlantic intertidal zone, for three weeks in hydroponic cultures subjected to various atmospheric CO<sub>2</sub> and O<sub>2</sub> concentrations. In doing so, they found that oxygen concentrations ranging from 10 to 200% of ambient had no significant effect on either the seaweed's daily net carbon gain or its total wet biomass production rate. In contrast, CO<sub>2</sub> concentrations ranging from 67 to 500% of ambient had highly significant effects on these parameters. At twice the ambient CO<sub>2</sub> concentration, for example, daily net carbon gain and total wet biomass production rates were 52 and 314% greater than they were at ambient CO<sub>2</sub>.

More recently, Zou (2005) collected specimens of the brown seaweed *Hizikia fusiforme* from intertidal rocks along the coast of Nanao Island, Shantou, China, and maintained them in glass

aquariums that contained filtered seawater enriched with 60  $\mu\text{M}$   $\text{NaNO}_3$  and 6.0  $\mu\text{M}$   $\text{NaH}_2\text{PO}_4$ , while continuously aerating the aquariums with air of either 360 or 700 ppm  $\text{CO}_2$  and periodically measuring seaweed growth and nitrogen assimilation rates, as well as nitrate reductase activities. By these means they determined that the slightly less than a doubling of the air's  $\text{CO}_2$  concentration increased the seaweed's mean relative growth rate by about 50%, its mean rate of nitrate uptake during the study's 12-hour light periods by some 200%, and its nitrate reductase activity by approximately 20% over a wide range of substrate nitrate concentrations.

As a subsidiary aspect of the study, Zou notes that "the extract of *H. fusiforme* has an immunomodulating activity on humans and this ability might be used for clinical application to treat several diseases such as tumors (Suetsuna, 1998; Shan *et al.*, 1999)." He also reports that the alga "has been used as a food delicacy and an herbal ingredient in China, Japan and Korea." In fact, he says that it "is now becoming one of the most important species for seaweed mariculture in China, owing to its high commercial value and increasing market demand." As a result, the ongoing rise in the air's  $\text{CO}_2$  content bodes well for all of these applications. In addition, Zou notes that "the intensive cultivation of *H. fusiforme* would remove nutrients more efficiently with the future elevation of  $\text{CO}_2$  levels in seawater, which could be a possible solution to the problem of ongoing coastal eutrophication," suggesting that rising  $\text{CO}_2$  levels may also assist in the amelioration of this environmental problem.

In light of these several observations, there is reason to believe that just as with freshwater macrophytes, the ongoing rise in the air's  $\text{CO}_2$  content should help marine macroalgae to become ever more productive with the passage of time.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/a/aquaticmacroalgae.php>.

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#### 6.1.3.4. Marine Microalgae

How do marine microalgae respond to increases in the air's CO<sub>2</sub> content? Based on the late 20th-century work of Riebesell *et al.* (1993), Hein and Sand-Jensen (1997) and Wolf-Gladrow *et al.*, (1999), it would appear that the productivity of earth's marine microalgae may be significantly enhanced by elevated concentrations of atmospheric CO<sub>2</sub>; and the more recent work of other researchers seems to suggest the same.

In a study of the unicellular marine diatom *Skeletonema costatum*, which is widely distributed in coastal waters throughout the world and is a major component of most natural assemblages of marine phytoplankton, Chen and Gao (2004) grew cell cultures of the species in filtered nutrient-enriched seawater maintained at 20°C under a light/dark cycle of 12/12 hours at a light intensity of 200  $\mu\text{mol m}^{-2} \text{s}^{-1}$ , while continuously aerating the culture solutions with air of either 350 or 1000 ppm CO<sub>2</sub> and measuring a number of physiological parameters related to the diatom's photosynthetic activity. They report that cell numbers of the alga "increased steadily throughout the light period and they were 1.6 and 2.1 times higher after the 12 h light period for the alga grown at 350 and 1000 ppm CO<sub>2</sub>, respectively." They also say that chlorophyll *a* concentrations "increased 4.4- and 5.4-fold during the middle 8 h of the light period for the alga grown at 350 and 1000 ppm CO<sub>2</sub>, respectively," and that "the contents of cellular chlorophyll *a* were higher for the alga grown at 1000 ppm CO<sub>2</sub> than that at 350 ppm CO<sub>2</sub>." In addition, they note that the initial slope of the light saturation curve of photosynthesis and the photochemical efficiency of photosystem II "increased with increasing CO<sub>2</sub>, indicating that the efficiency of light-harvesting and energy conversion in photosynthesis were increased." The end result of these several responses, in the words of Chen and Gao, was that "*S. costatum* benefited from CO<sub>2</sub> enrichment."

In another report of a study of marine microalgae that would appear to have *enormous* implications, Gordillo *et al.* (2003) begin by noting that "one of the main queries for depicting future scenarios of evolution of atmospheric composition and temperature is whether an atmospheric CO<sub>2</sub> increase stimulates primary production, especially in aquatic plants." Why do they say that? They say it *because*, as they put it, "aquatic primary producers account for about 50% of the total carbon fixation in the biosphere (Falkowski and Raven, 1997)."

Although the question addressed by Gordillo *et al.* sounds simple enough, its answer is not straightforward. In many phytoplankton, both freshwater and marine, photosynthesis appears to be saturated under current environmental conditions. Raven (1991), however, has suggested that those very same species, many of which employ carbon-concentrating mechanisms, could well decrease the amount of energy they expend in this latter activity in a CO<sub>2</sub>-enriched world, which metabolic readjustment would leave a larger proportion of their captured energy available for fueling enhanced growth.

To explore this possibility, the four researchers studied various aspects of the growth response of the microalgal chlorophyte *Dunaliella viridis* (which possesses a carbon concentrating mechanism and has been used as a model species for the study of inorganic carbon uptake) to atmospheric CO<sub>2</sub> enrichment. Specifically, they batch-cultured the chlorophyte, which is one of the most ubiquitous eukaryotic organisms in hypersaline environments, in 250-ml Perspex cylinders under controlled laboratory conditions at high (5 mM) and low (0.5 mM) nitrate concentrations, while continuously aerating half of the cultures with ambient air of approximately 350 ppm CO<sub>2</sub> and the other half with air of approximately 10,000 ppm CO<sub>2</sub>. In doing so, they discovered that atmospheric CO<sub>2</sub> enrichment had little effect on dark respiration in both N treatments. Likewise, it had little effect on photosynthesis in the low-N treatment. In the high-N treatment, on the other hand, the extra CO<sub>2</sub> increased photosynthesis by 114%. In the case of biomass production, the results were even more extreme: in the low-N treatment elevated CO<sub>2</sub> had no effect at all, while in the high-N treatment it nearly *tripled* the cell density of the culture solution.

In discussing their findings, Gordillo *et al.* note that "it has long been debated whether phytoplankton species are growth-limited by current levels of CO<sub>2</sub> in aquatic systems, i.e. whether an increase in atmospheric CO<sub>2</sub> could stimulate growth (Riebesell *et al.*, 1993)." Their results clearly indicate that it can, as long as sufficient nitrogen is available. But that was not all that Gordillo *et al.* learned. In the high-N treatment, where elevated CO<sub>2</sub> greatly stimulated photosynthesis and biomass production, once the logarithmic growth phase had run its course and equilibrium growth was attained, approximately 70% of the carbon assimilated by the chlorophyte was released to the water, while in the low-CO<sub>2</sub> treatment only 35% was released.

With respect to this suite of observations, Gordillo *et al.* say "the release of organic carbon to the external medium has been proposed as a mechanism for maintaining the metabolic integrity of the cell (Ormerod, 1983)," and that "according to Wood and Van Valen (1990), organic carbon release would be a sink mechanism protecting the photosynthetic apparatus from an overload of products that cannot be invested in growth or stored." They additionally



state that stores of photosynthetic products "are reduced to avoid overload and produce a high demand for photosynthates." Under these conditions, they conclude that "the process would then divert assimilated C to either the production of new biomass, or the release to the external medium once the culture conditions do not allow further exponential growth."

A second consequence of enhanced organic carbon release in the face of atmospheric CO<sub>2</sub> enrichment and sufficient N availability is that the internal C:N balance of the phytoplankton is maintained within a rather tight range. Even more exciting is the fact that this phenomenon has also been observed in the green seaweed *Ulva rigida* (Gordillo *et al.*, 2001) and the cyanobacterium *Spirulina platensis* (Gordillo *et al.*, 1999). Hence, what the study of Gordillo *et al.* implies about the response of *Dunaliella viridis* to atmospheric CO<sub>2</sub> enrichment may well be widely applicable to many, if not most, aquatic plants, not the least of which may be the zooxanthellae that by this means (enhanced organic carbon release) could provide their coral hosts with the source of extra energy they need to continue building their skeletons at a non-reduced rate in the face of the negative calcification pressure produced by the changes in seawater chemistry that have been predicted to result from the ongoing rise in the air's CO<sub>2</sub> concentration.

In light of these several observations, there would appear to be ample reason to be optimistic about the response of earth's marine macroalgae to the ongoing rise in the air's CO<sub>2</sub> content.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/a/aquaticmicroalgae.php>.

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## **6.2. Water Use Efficiency**

Another major consequence of atmospheric CO<sub>2</sub> enrichment is that plants exposed to elevated levels of atmospheric CO<sub>2</sub> generally do not open their leaf stomatal pores – through which they take in carbon dioxide and give off water vapor – as wide as they do at lower CO<sub>2</sub> concentrations. In addition, they tend to produce less of these pores per unit area of leaf surface at higher levels of atmospheric CO<sub>2</sub>. Both of these changes tend to reduce most plants' rates of water loss by transpiration; and the amount of carbon they gain per unit of water lost – or water-use efficiency – therefore typically rises, greatly increasing their ability to withstand drought. And with fewer and smaller stomatal openings, plants exposed to elevated levels of atmospheric CO<sub>2</sub> are also less susceptible to damage by noxious air pollutants – including ozone and oxides of nitrogen and sulfur – that gain entry into plants via these portals. In this section, we explore the phenomena of water use efficiency as it pertains to agricultural, grassland and woody species.

Additional information on this topic, including reviews water use efficiency not discussed here, can be found at [http://www.co2science.org/subject/w/subject\\_w.php](http://www.co2science.org/subject/w/subject_w.php) under the heading Water Use Efficiency.

### **6.2.1. Agricultural Species**

In the study of Serraj *et al.* (1999), soybeans grown at 700 ppm CO<sub>2</sub> displayed 10 to 25% reductions in total water loss while simultaneously exhibiting increases in dry weight of as much as 33%. Thus, elevated CO<sub>2</sub> significantly increased the water-use efficiencies of the

studied plants. Likewise, Garcia *et al.* (1998) determined that spring wheat grown at 550 ppm CO<sub>2</sub> exhibited a water-use efficiency that was about one-third greater than that exhibited by plants grown at 370 ppm CO<sub>2</sub>. Similarly, Hakala *et al.* (1999) reported that twice-ambient CO<sub>2</sub> concentrations increased the water-use efficiency of spring wheat by 70 to 100%, depending on experimental air temperature. In addition, Hunsaker *et al.* (2000) reported CO<sub>2</sub>-induced increases in water-use efficiency for field-grown wheat that were 20 and 10% higher than those displayed by ambiently-grown wheat subjected to high and low soil nitrogen regimes, respectively. Also, pea plants grown for two months in growth chambers receiving atmospheric CO<sub>2</sub> concentrations of 700 ppm displayed an average water-use efficiency that was 27% greater than that exhibited by ambiently-grown control plants (Gavito *et al.*, 2000).

In some cases, the water-use efficiency increases caused by atmospheric CO<sub>2</sub> enrichment are spectacularly high. De Luis *et al.* (1999), for example, demonstrated that alfalfa plants subjected to atmospheric CO<sub>2</sub> concentrations of 700 ppm had water-use efficiencies that were 2.6 and 4.1 times greater than those displayed by control plants growing at 400 ppm CO<sub>2</sub> under water-stressed and well-watered conditions, respectively. Also, when grown at an atmospheric CO<sub>2</sub> concentration of 700 ppm, a 2.7-fold increase in water-use efficiency was reported by Malmstrom and Field (1997) for oats infected with the barley yellow dwarf virus.

In addition to enhancing the water-use efficiencies of agricultural C<sub>3</sub> crops, as reported in the preceding paragraphs, elevated CO<sub>2</sub> also enhances the water-use efficiencies of crops possessing alternate carbon fixation pathways. Maroco *et al.* (1999), for example, demonstrated that maize - a C<sub>4</sub> crop - grown for 30 days at an atmospheric CO<sub>2</sub> concentration of 1100 ppm exhibited an intrinsic water-use efficiency that was 225% higher than that of plants grown at 350 ppm CO<sub>2</sub>. In addition, Conley *et al.* (2001) reported that a 200-ppm increase in the air's CO<sub>2</sub> content boosted the water-use efficiency of field-grown sorghum by 9 and 19% under well-watered and water-stressed conditions, respectively. Also, Zhu *et al.* (1999) reported that pineapple - a CAM plant - grown at 700 ppm CO<sub>2</sub> exhibited water-use efficiencies that were always significantly greater than those displayed by control plants grown at 350 ppm CO<sub>2</sub> over a range of growth temperatures.

It is clear from the studies above that as the CO<sub>2</sub> content of the air continues to rise, nearly all of earth's agricultural species will respond favorably by exhibiting increases in water-use efficiency. It is thus likely that food and fiber production will increase on a worldwide basis, even in areas where productivity is severely restricted due to limited availability of soil moisture. Therefore, one can expect global agricultural productivity to rise in tandem with future increases in the atmosphere's CO<sub>2</sub> concentration.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/w/wateruseag.php>.

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### 6.2.2. Grassland Species

In the study of Grunzweig and Korner (2001), model grasslands representative of the semi-arid Negev of Israel, which were grown for five months at atmospheric CO<sub>2</sub> concentrations of 440 and 600 ppm, exhibited cumulative water-use efficiencies that were 17 and 28% greater, respectively, than control communities grown at 280 ppm CO<sub>2</sub>. Similarly, Szente *et al.* (1998) reported a doubling of the atmospheric CO<sub>2</sub> concentration increased the water-use efficiency

two C<sub>3</sub> grasses and two broad-leaved species common to the loess grasslands of Budapest by 72 and 266%, respectively. In addition, Leymarie *et al.* (1999) calculated that twice-ambient CO<sub>2</sub> concentrations increased the water-use efficiency of the herbaceous weedy species *Arabidopsis thaliana* by 41 and 120% under well-watered and water-stressed conditions, respectively. Other CO<sub>2</sub>-induced increases in C<sub>3</sub> plant water-use efficiency have been documented by Clark *et al.* (1999) for several New Zealand pasture species and Roumet *et al.* (2000) for various Mediterranean herbs.

Elevated CO<sub>2</sub> has also been shown to substantially increase the water-use efficiency of C<sub>4</sub> grassland species. Adams *et al.* (2000), for example, reported that twice-ambient CO<sub>2</sub> concentrations enhanced the daily water-use efficiency of a C<sub>4</sub> tallgrass prairie in Kansas, USA, dominated by *Andropogon gerardii*. LeCain and Morgan (1998) also documented enhanced water-use efficiencies for six different C<sub>4</sub> grasses grown with twice-ambient CO<sub>2</sub> concentrations. Likewise, Seneweera *et al.* (1998) reported that a 650-ppm increase in the air's CO<sub>2</sub> content dramatically increased the water-use efficiency of the perennial C<sub>4</sub> grass *Panicum coloratum*.

As the air's CO<sub>2</sub> content continues to rise, nearly all of earth's grassland species - including both C<sub>3</sub> and C<sub>4</sub> plants - will likely experience increases in water-use efficiency. Concomitantly, the productivity of the world's grasslands should also increase, even if available moisture decreases in certain areas. Moreover, such CO<sub>2</sub>-induced increases in water-use efficiency will likely allow grassland species to expand their ranges into desert areas where they previously could not survive due to lack of sufficient moisture. Thus, this phenomenon will likely contribute to a greater "greening of the globe."

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/w/waterusegrass.php>.

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### 6.2.3. Woody Species

The effect of elevated atmospheric CO<sub>2</sub> concentrations on the water-use efficiencies of trees is clearly positive, having been documented in a number of different single-species studies of longleaf pine (Runion *et al.*, 1999), red oak (Anderson and Tomlinson, 1998), scrub oak (Lodge *et al.*, 2001), silver birch (Rey and Jarvis, 1998), beech (Bucher-Wallin *et al.*, 2000; Egli *et al.*, 1998), sweetgum (Gunderson *et al.*, 2002; Wullschlegler and Norby, 2001) and spruce (Roberntz and Stockfors, 1998). Likewise, in a multi-species study performed by Tjoelker *et al.* (1998), seedlings of quaking aspen, paper birch, tamarack, black spruce and jack pine, which were grown at 580 ppm CO<sub>2</sub> for three months, displayed water-use efficiencies that were 40 to 80% larger than those exhibited by their respective controls grown at 370 ppm CO<sub>2</sub>.

Similar results are also obtained when trees are exposed to different environmental stresses. In a study conducted by Centritto *et al.* (1999), for example, cherry seedlings grown at twice-ambient levels of atmospheric CO<sub>2</sub> displayed water-use efficiencies that were 50% greater than their ambient controls, regardless of soil moisture status. And in the study of Wayne *et al.* (1998), yellow birch seedlings grown at 800 ppm CO<sub>2</sub> had water-use efficiencies that were 52 and 94% greater than their respective controls, while simultaneously subjected to uncharacteristically low and high air temperature regimes.

In some parts of the world, perennial woody species have been exposed to elevated atmospheric CO<sub>2</sub> concentrations for decades, due to their proximity to CO<sub>2</sub>-emitting springs and vents in the earth, allowing scientists to assess the long-term effects of this phenomenon. In Venezuela, for example, the water-use efficiency of a common tree exposed to a lifetime atmospheric CO<sub>2</sub> concentration of approximately 1,000 ppm rose 2-fold and 19-fold during the local wet and dry seasons, respectively (Fernandez *et al.*, 1998). Similarly, Bartak *et al.* (1999) reported that 30-year-old *Arbutus unedo* trees growing in central Italy at a lifetime atmospheric CO<sub>2</sub> concentration around 465 ppm exhibited water-use efficiencies that were 100% greater than control trees growing at a lifetime CO<sub>2</sub> concentration of 355 ppm. In addition, two species

of oaks in central Italy that had been growing for 15 to 25 years at an atmospheric CO<sub>2</sub> concentration ranging from 500 to 1000 ppm displayed "such marked increases in water-use efficiency under elevated CO<sub>2</sub>," in the words of the scientists who studied them, that this phenomenon "might be of great importance in Mediterranean environments in the perspective of global climate change" (Blaschke *et al.*, 2001; Tognetti *et al.*, 1998). Thus, the long-term effects of elevated CO<sub>2</sub> concentrations on water-use efficiency are likely to persist and increase with increasing atmospheric CO<sub>2</sub> concentrations.

In some cases, scientists have looked to the past and determined the positive impact the historic rise in the air's CO<sub>2</sub> content has already had on plant water-use efficiency. Duquesnay *et al.* (1998), for example, used tree-ring data derived from beech trees to determine that over the past century the water-use efficiency of such trees in north-eastern France increased by approximately 33%. Similarly, Feng (1999) used tree-ring chronologies derived from a number of trees in western North America to calculate a 10 to 25% increase in tree water-use efficiency from 1750 to 1970, during which time the atmospheric CO<sub>2</sub> concentration rose by approximately 16%. In another study, Knapp *et al.* (2001) developed tree-ring chronologies from western juniper stands located in Oregon, USA, for the past century, determining that growth recovery from drought was much greater in the latter third of their chronologies (1964-1998) than it was in the first third (1896-1930). In this case, the authors suggested that the greater atmospheric CO<sub>2</sub> concentrations of the latter period allowed the trees to more quickly recover from water stress. Finally, Beerling *et al.* (1998) grew *Gingko* saplings at 350 and 650 ppm CO<sub>2</sub> for three years, finding that elevated atmospheric CO<sub>2</sub> concentrations reduced leaf stomatal densities to values comparable to those measured on fossilized *Gingko* leaves dating back to the Triassic and Jurassic periods, implying greater water-use efficiencies for those times too.

On another note, Prince *et al.* (1998) demonstrated that rain-use efficiency, which is similar to water-use efficiency, slowly increased in the African Sahel from 1982 to 1990, while Nicholson *et al.* (1998) observed neither an increase nor a decrease in this parameter from 1980 to 1995 for the central and western Sahel.

In summary, it is clear that as the CO<sub>2</sub> content of the air continues to rise, nearly all of earth's trees will respond favorably by exhibiting increases in water-use efficiency. It is thus likely that as time progresses, earth's woody species will expand into areas where they previously could not exist due to limiting amounts of available moisture. Therefore, one can expect the earth to become a greener biospheric body with greater carbon sequestering capacity as the atmospheric CO<sub>2</sub> concentration continues to rise.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/w/waterusetrees.php>.

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### **6.3. Amelioration of Environmental Stresses**

Atmospheric CO<sub>2</sub> enrichment has also been shown to help ameliorate the detrimental effects of several environmental stresses on plant growth and development, including high soil salinity, high air temperature, low light intensity and low levels of soil fertility. Elevated levels of CO<sub>2</sub> have additionally been demonstrated to reduce the severity of low temperature stress, oxidative stress, and the stress of herbivory. In fact, the percentage growth enhancement produced by an increase in the air's CO<sub>2</sub> concentration is generally even greater under stressful and resource-limited conditions than it is when growing conditions are ideal. In this section we examine several such benefits that the rise in atmospheric CO<sub>2</sub> portends for the biosphere.

Additional information on this topic, including reviews on stresses not discussed here, can be found at [http://www.co2science.org/subject/g/subject\\_g.php](http://www.co2science.org/subject/g/subject_g.php) under the heading Growth Response to CO<sub>2</sub> with Other Variables.

#### **6.3.1. Disease**

As the air's CO<sub>2</sub> content continues to rise, nearly all of earth's plants should continue to exhibit increasing rates of photosynthesis and, as a result, increased biomass production. But what about plants that are suffering from various pathogenic diseases? Will they be able to reap the benefits of the many positive effects of atmospheric CO<sub>2</sub> enrichment?

We begin our exploration of this important subject with some introductory comments of Chakraborty and Datta (2003), who note there are a number of CO<sub>2</sub>-induced changes in plant physiology, anatomy and morphology that have been implicated in increased plant resistance to disease and that "can potentially enhance host resistance at elevated CO<sub>2</sub>," among which phenomena they list "increased net photosynthesis allowing mobilization of resources into host resistance (Hibberd *et al.*, 1996a.); reduced stomatal density and conductance (Hibberd *et al.*, 1996b); greater accumulation of carbohydrates in leaves; more waxes, extra layers of epidermal cells and increased fibre content (Owensby, 1994); production of papillae and accumulation of silicon at penetration sites (Hibberd *et al.*, 1996a); greater number of mesophyll cells (Bowes, 1993); and increased biosynthesis of phenolics (Hartley *et al.*, 2000), among others." In what follows, we summarize the findings of some additional studies we have reviewed on our website that have dealt with these and other related phenomena.

Malmstrom and Field (1997) grew individual oat plants for two months in pots placed within phytocells maintained at atmospheric CO<sub>2</sub> concentrations of 350 and 700 ppm, while they infected one-third of the plants with the barley yellow dwarf virus (BYDV), which plagues more than 150 plant species worldwide, including all major cereal crops. Over the course of their study, they found that elevated CO<sub>2</sub> stimulated rates of net photosynthesis in all plants, regardless of pathogen infection. However, the greatest percentage increase occurred in diseased individuals (48% vs. 34%). Moreover, atmospheric CO<sub>2</sub> enrichment decreased stomatal conductance by 50% in infected plants but by only 34% in healthy ones, which led to a CO<sub>2</sub>-induced doubling of the instantaneous water-use efficiency of the healthy plants, but an

increase of fully 2.7-fold in the diseased plants. Last of all, after 60 days of growth under these conditions, they determined that the extra CO<sub>2</sub> increased total plant biomass by 36% in infected plants, but by only 12% in healthy plants. In addition, while elevated CO<sub>2</sub> had little effect on root growth in the healthy plants, it increased root biomass in the infected plants by up to 60%. Consequently, it can be appreciated that as the CO<sub>2</sub> content of the air continues to rise, its many positive effects will likely offset some, if not most, of the negative effects of the destructive BYDV. Quoting Malmstrom and Field with respect to two specific examples, they say in their concluding remarks that CO<sub>2</sub> enrichment "may reduce losses of infected plants to drought" and "may enable diseased plants to compete better with healthy neighbors."

Tiedemann and Firsching (2000) grew spring wheat plants from germination to maturity in controlled-environment chambers maintained at ambient (377 ppm) and elevated (612 ppm) concentrations of atmospheric CO<sub>2</sub> and at ambient (20 ppb) and elevated (61 ppb) concentrations of ozone (and combinations thereof), the latter of which gases is typically toxic to most plants. In addition, half of the plants in each treatment were inoculated with a leaf rust-causing fungus. Under these conditions, the elevated CO<sub>2</sub> increased the photosynthetic rates of the diseased plants by 20 and 42% at the ambient and elevated ozone concentrations, respectively. It also enhanced the yield of the infected plants, increasing it by 57%, even in the presence of high ozone concentrations.

Jwa and Walling (2001) grew tomato plants hydroponically for eight weeks in controlled-environment chambers maintained at atmospheric CO<sub>2</sub> concentrations of 350 and 700 ppm. In addition, at week five of the study, half of all plants growing in each CO<sub>2</sub> concentration were infected with a fungal pathogen that attacks plant roots and induces a water stress that decreases growth and yield. At the end of the study, they found that the pathogenic infection had reduced total plant biomass by nearly 30% at both atmospheric CO<sub>2</sub> concentrations. However, the elevated CO<sub>2</sub> had increased the total biomass of the healthy and diseased plants by the same amount (+30%), with the result that the *infected* tomato plants grown at 700 ppm CO<sub>2</sub> had biomass values that were essentially identical to those of the *healthy* tomato plants grown at 350 ppm CO<sub>2</sub>. Thus, the extra CO<sub>2</sub> *completely counterbalanced* the negative effect of the pathogenic infection on overall plant productivity.

Chakraborty and Datta (2003) studied the aggressiveness of the fungal anthracnose pathogen *Colletotrichum gloeosporioides* by inoculating two isolates of the pathogen onto two cultivars of the tropical pasture legume *Stylosanthes scabra* (Fitzroy, which is susceptible to the fungal pathogen, and Seca, which is more resistant) over 25 sequential infection cycles in controlled-environment chambers filled with air of either 350 or 700 ppm CO<sub>2</sub>. By these means they determined that the aggressiveness of the pathogen was reduced at the twice-ambient level of atmospheric CO<sub>2</sub>, where *aggressiveness* is defined as "a property of the pathogen reflecting the relative amount of damage caused to the host without regard to resistance genes (Shaner *et al.*, 1992)." As they describe it, "at twice-ambient CO<sub>2</sub> the overall level of aggressiveness of the two [pathogen] isolates was significantly reduced on both cultivars."

Simultaneously, however, pathogen *fecundity* was found to *increase* at twice-ambient CO<sub>2</sub>. Of this finding, Chakraborty and Datta report that their results "concur with the handful of studies that have demonstrated increased pathogen fecundity at elevated CO<sub>2</sub> (Hibberd *et al.*, 1996a; Klironomos *et al.*, 1997; Chakraborty *et al.*, 2000)." How this happened in the situation they investigated, according to Chakraborty and Datta, is that the overall increase in fecundity at high CO<sub>2</sub> "is a reflection of the altered canopy environment," wherein "the 30% larger *S. scabra* plants at high CO<sub>2</sub> (Chakraborty *et al.*, 2000) makes the canopy microclimate more conducive to anthracnose development."

In view of these opposing changes in pathogen behavior at elevated levels of atmospheric CO<sub>2</sub>, it is difficult to know the ultimate outcome of atmospheric CO<sub>2</sub> enrichment for this specific pathogen-host relationship. More research, especially under realistic field conditions, will be needed to clarify the situation; and, of course, different results are likely to be observed for different pathogen-host associations. What is more, results could also differ under different climatic conditions. Nevertheless, the large number of ways in which elevated CO<sub>2</sub> has been demonstrated to increase plant resistance to pathogen attack gives us reason to believe that plants will gain the advantage as the air's CO<sub>2</sub> content continues to climb in the years ahead.

Another study that fuels this optimism was conducted by Parsons *et al.* (2003), who grew two-year-old saplings of paper birch and three-year-old saplings of sugar maple in well-watered and fertilized pots from early May until late August in glasshouse rooms maintained at either 400 or 700 ppm CO<sub>2</sub>. In these circumstances, the whole-plant biomass of paper birch was increased by 55% in the CO<sub>2</sub>-enriched portions of the glasshouse, while that of sugar maple was increased by 30%. Also, concentrations of condensed tannins were increased by 27% in the paper birch (but not the sugar maple) saplings grown in the CO<sub>2</sub>-enriched air; and in light of this finding, Parsons *et al.* conclude that "the higher condensed tannin concentrations that were present in the birch fine roots may offer these tissues greater protection against soil-borne pathogens and herbivores."

Within this context, it is interesting to note that Parsons *et al.* report that CO<sub>2</sub>-induced increases in fine root concentrations of total phenolics and condensed tannins have also been observed in warm temperate conifers by King *et al.* (1997), Entry *et al.* (1998), Gebauer *et al.* (1998) and Runion *et al.* (1999), as well as in cotton by Booker (2000).

In another intriguing study, Gamper *et al.* (2004) begin by noting that arbuscular mycorrhizal fungi (AMF) are expected to modulate plant responses to elevated CO<sub>2</sub> by "increasing resistance/tolerance of plants against an array of environmental stressors (Smith and Read, 1997)." In investigating this subject in a set of experiments conducted over a seven-year period of free-air CO<sub>2</sub>-enrichment on two of the world's most extensively grown cool-season forage crops (*Lolium perenne* and *Trifolium repens*) at the Swiss FACE facility near Zurich, they determined that "at elevated CO<sub>2</sub> and under [two] N treatments, AMF root colonization of both host plant species was increased," and that "colonization levels of all three measured intraradical AMF structures (hyphae, arbuscules and vesicles) tended to be higher." Hence, they

concluded that these CO<sub>2</sub>-induced benefits may lead to "increased protection against pathogens and/or herbivores."

Pangga *et al.* (2004) grew well-watered and fertilized seedlings of a cultivar (Fitzroy) of the pencilflower (*Stylosanthes scabra*) -- an important legume crop that is susceptible to anthracnose disease caused by *Colletotrichum gloeosporioides* (Penz.) Penz. & Sacc. -- within a controlled environment facility maintained at atmospheric CO<sub>2</sub> concentrations of either 350 or 700 ppm, where they inoculated six-, nine- and twelve-week-old plants with conidia of *C. gloeosporioides*. Then, ten days after inoculation, they counted the anthracnose lesions on the plants and classified them as either resistant or susceptible.

Adherence to this protocol revealed, in their words, that "the mean number of susceptible, resistant, and total lesions per leaf averaged over the three plant ages was significantly ( $P < 0.05$ ) greater at 350 ppm than at 700 ppm CO<sub>2</sub>, reflecting the development of a level of resistance in susceptible cv. Fitzroy at high CO<sub>2</sub>." In fact, with respect to the plants inoculated at twelve weeks of age, they say that those grown "at 350 ppm had 60 and 75% more susceptible and resistant lesions per leaf, respectively, than those [grown] at 700 ppm CO<sub>2</sub>."

In terms of *infection efficiency* (IE), the Australian scientists say their work "clearly shows that at 350 ppm overall susceptibility of the canopy increases with increasing age because more young leaves are produced on secondary and tertiary branches of the more advanced plants." However, they report that "at 700 ppm CO<sub>2</sub>, IE did not increase with increasing plant age despite the presence of many more young leaves in the enlarged canopy," which finding, in their words, "points to reduced pathogen efficiency or an induced partial resistance to anthracnose in Fitzroy at 700 ppm CO<sub>2</sub>." Consequently, as the air's CO<sub>2</sub> content continues to rise, it would appear that the Fitzroy cultivar of the pasture legume *Stylosanthes scabra* will indeed acquire a greater intrinsic resistance to the devastating anthracnose disease.

McElrone *et al.* (2005) "assessed how elevated CO<sub>2</sub> affects a foliar fungal pathogen, *Phyllosticta minima*, of *Acer rubrum* [red maple] growing in the understory at the Duke Forest free-air CO<sub>2</sub> enrichment experiment in Durham, North Carolina, USA ... in the 6th, 7th, and 8th years of the CO<sub>2</sub> exposure." Surveys conducted in those years, in their words, "revealed that elevated CO<sub>2</sub> [to 200 ppm above ambient] significantly reduced disease incidence, with 22%, 27% and 8% fewer saplings and 14%, 4%, and 5% fewer leaves infected per plant in the three consecutive years, respectively." In addition, they report that the elevated CO<sub>2</sub> "also significantly reduced disease severity in infected plants in all years (e.g. mean lesion area reduced 35%, 50%, and 10% in 2002, 2003, and 2004, respectively)."

What underlying mechanism or mechanisms produced these beneficent consequences? Thinking it could have been a direct deleterious effect of elevated CO<sub>2</sub> on the fungal pathogen, McElrone *et al.* performed some side experiments in controlled environment chambers. However, they found that the elevated CO<sub>2</sub> benefited the fungal pathogen as well as the red maple saplings, observing that "exponential growth rates of *P. minima* were 17% greater under

elevated CO<sub>2</sub>." And they obtained similar results when they repeated the *in vitro* growth analysis two additional times in different growth chambers.

Taking another tack when "scanning electron micrographs verified that conidia germ tubes of *P. minima* infect *A. rubrum* leaves by entering through the stomata," the researchers turned their attention to the pathogen's mode of entry into the saplings' foliage. In this investigation they found that both stomatal size and density were unaffected by atmospheric CO<sub>2</sub> enrichment, but that "stomatal conductance was reduced by 21-36% under elevated CO<sub>2</sub>, providing smaller openings for infecting germ tubes." In addition, they concluded that reduced disease severity under elevated CO<sub>2</sub> was also likely due to altered leaf chemistry, as elevated CO<sub>2</sub> increased total leaf phenolic concentrations by 15% and tannin concentrations by 14%.

Because the phenomena they found to be important in reducing the amount and severity of fungal pathogen infection (leaf spot disease) of red maple have been demonstrated to be operative in most other plants as well, McElrone *et al.* say these CO<sub>2</sub>-enhanced leaf defensive mechanisms "may be prevalent in many plant pathosystems where the pathogen targets the stomata." Indeed, they state that their results "provide concrete evidence for a potentially generalizable mechanism to predict disease outcomes in other pathosystems under future climatic conditions." And because of their insightful work, that future is looking particularly bright in terms of the never-ending struggle between earth's plants and the pathogens that prey upon them. Although elevated CO<sub>2</sub> helps *both* sides of the conflict, it helps plants *more* and in *more ways*.

Matros *et al.* (2006) grew tobacco plants (*Nicotiana tabacum* L.) in 16-cm-diameter pots filled with quartz sand in controlled-climate chambers maintained at either 350 or 1000 ppm CO<sub>2</sub> for a period of eight weeks, where they were irrigated daily with a complete nutrient solution containing either 5 or 8 mM NH<sub>4</sub>NO<sub>3</sub>. In addition, some of the plants in each treatment were mechanically infected with the *potato virus Y* (PVY) when they were six weeks old. Then, at the end of the study, the plants were harvested and a number of their chemical constituents identified and quantified.

This work revealed, in the researchers words, that "plants grown at elevated CO<sub>2</sub> and 5 mM NH<sub>4</sub>NO<sub>3</sub> showed a marked and significant decrease in content of nicotine in leaves as well as in roots," while at 8 mM NH<sub>4</sub>NO<sub>3</sub> the same was found to be true of upper leaves but not of lower leaves and roots. With respect to the PVY part of the study, they further report that the "plants grown at high CO<sub>2</sub> showed a markedly decreased spread of virus." Both of these findings would likely be considered beneficial by most people, as *potato virus Y* is an economically important virus that infects many crops and ornamental plants throughout the world, while nicotine is nearly universally acknowledged to have significant negative impacts on human health (Topliss *et al.*, 2002).

Braga *et al.* (2006) conducted three independent experiments where they grew well-watered soybean (*Glycine max* (L.) Merr) plants of two cultivars (IAC-14, susceptible to stem canker disease, and IAC-18, resistant to stem canker disease) from seed through the cotyledon stage in

5-liter pots placed within open-top chambers maintained at atmospheric CO<sub>2</sub> concentrations of either 360 or 720 ppm in a glasshouse, while they measured various plant properties and processes, concentrating on the production of *glyceollins* (the major *phytoalexins*, or antimicrobial compounds, produced in soybeans) in response to the application of β-glucan elicitor (derived from mycelial walls of *Phytophthora sojae*) to carefully created and replicated wounds in the surfaces of several soybean cotyledons. In doing so, they found that the IAC-14 cultivar did *not* exhibit a CO<sub>2</sub>-induced change in glyceollin production in response to elicitation - as Braga *et al.* had hypothesized would be the case, since this cultivar is susceptible to stem canker disease -- but they found that the IAC-18 cultivar (which has the potential to resist the disease to varying degrees) experienced a 100% CO<sub>2</sub>-induced increase in the amount of glyceollins produced after elicitation, a response the researchers described as *remarkable*. As for its significance, Braga *et al.* say the CO<sub>2</sub>-induced response they observed "may increase the potential of the soybean defense since infection at early stages of plant development, followed by a long incubation period before symptoms appear, is characteristic of the stem canker disease cycle caused by Dpm [*Diaporthe phaseolorum* (Cooke & Ellis) Sacc. f. sp. *meridionalis* Morgan-Jones]." Hence, they say the response they observed "indicates that raised CO<sub>2</sub> levels forecasted for next decades may have a real impact on the defensive chemistry of the cultivars."

Last of all, in a study conducted within the BioCON (Biodiversity, Carbon dioxide, and Nitrogen effects on ecosystem functioning) FACE facility located at the Cedar Creek Natural History Area in east-central Minnesota, USA, Strengbom and Reich (2006) evaluated the effects of an approximate 190-ppm increase in the air's daytime CO<sub>2</sub> concentration on leaf photosynthetic rates of stiff goldenrod (*Solidago rigida*) growing in monoculture for two full seasons, together with its concomitant effects on the incidence and severity of leaf spot disease. Although they found that elevated CO<sub>2</sub> had no significant effect on plant photosynthetic rate in their study, they report that "both disease incidence and severity were lower on plants grown under elevated CO<sub>2</sub>." More specifically, they found that "disease incidence was on average *more than twice as high* [our italics] under ambient as under elevated CO<sub>2</sub>," and that "disease severity (proportion of leaf area with lesions) was on average 67% lower under elevated CO<sub>2</sub> compared to ambient conditions."

In discussing their results, Strengbom and Reich say the "indirect effects from elevated CO<sub>2</sub>, i.e., lower disease incidence, had a stronger effect on realized photosynthetic rate than the direct effect of higher CO<sub>2</sub>," which as noted above was negligible in their study. Hence, they conclude "it may be necessary to consider potential changes in susceptibility to foliar diseases to correctly estimate the effects on plant photosynthetic rates of elevated CO<sub>2</sub>." In addition, they note that the plants grown in CO<sub>2</sub>-enriched air had lower leaf nitrogen concentrations than the plants grown in ambient air, as is often observed in studies of this type; and they say that their results "are, thus, also in accordance with other studies that have found reduced pathogen performance following reduced nitrogen concentration in plants grown under elevated CO<sub>2</sub> (Thompson and Drake, 1994)." What is more, they conclude that their results are "also in accordance with studies that have found increased [disease] susceptibility following increased nitrogen concentration of host plants (Huber and Watson, 1974; Nordin *et al.*, 1998; Strengbom

*et al.*, 2002)." It is possible, therefore, that the ongoing rise in the air's CO<sub>2</sub> content may help many plants of the future reduce the deleterious impacts of various pathogenic fungal diseases that currently beset them, thereby enabling them to increase their productivities above and beyond what is typically provided by the more direct growth stimulation resulting from the aerial fertilization effect of elevated atmospheric CO<sub>2</sub> concentrations.

In summation, the vast bulk of the available data clearly suggests that atmospheric CO<sub>2</sub> enrichment asserts its greatest positive influence on *infected* as opposed to *healthy* plants. Moreover, it would appear that elevated CO<sub>2</sub> has the ability to significantly ameliorate the deleterious effects of various stresses imposed upon plants by numerous pathogenic invaders. Consequently, as the atmosphere's CO<sub>2</sub> concentration continues its upward climb, earth's vegetation should be increasingly better equipped to successfully deal with pathogenic organisms and the damage they have traditionally done to humanity's crops, as well as to the plants that sustain the rest of the planet's animal life.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/g/disease.php>.

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### 6.3.2. Herbivory

Insect pests have greatly vexed earth's plants in the past and will likely continue to do so in the future. It is possible, however, that the ongoing rise in the atmosphere's CO<sub>2</sub> content may impact this phenomenon, for better or for worse. Consequently, in this section we review the results of several studies that have addressed this subject as it applies to herbaceous and woody plants.

Additional information on this topic, including reviews on herbivory not discussed here, can be found at [http://www.co2science.org/subject/h/subject\\_h.php](http://www.co2science.org/subject/h/subject_h.php) under the heading Herbivory.

#### 6.3.2.1. Herbaceous Plants

Kerslake *et al.* (1998) grew five-year-old heather (*Calluna vulgaris*) plants collected from a Scottish moor in open-top chambers maintained at atmospheric CO<sub>2</sub> concentrations of 350 and

600 ppm. At two different times during the study, larvae of the destructive winter moth *Operophtera brumata* -- whose outbreaks periodically cause extensive damage to heather moorland -- were allowed to feed upon current-year shoots. Feeding upon the high-CO<sub>2</sub>-grown foliage did not affect larval growth rates, development or final pupal weights; neither was moth survivorship significantly altered. Hence, the authors concluded that their study "provides no evidence that increasing atmospheric CO<sub>2</sub> concentrations will affect the potential for outbreak of *Operophtera brumata* on this host." What it did show, however, was a significant CO<sub>2</sub>-induced increase in heather water use efficiency.

Newman *et al.* (1999) inoculated tall fescue (*Festuca arundinacea*) plants growing in open-top chambers maintained at atmospheric CO<sub>2</sub> concentrations of 350 and 700 ppm with bird cherry-oat aphids (*Rhopalosiphum padi*). After nine weeks, the plants growing in the CO<sub>2</sub>-enriched air had experienced a 37% increase in productivity and were covered with far fewer aphids than the plants growing in ambient air. The result, therefore, was a win for the favored plants and a loss for the destructive insects.

Goverde *et al.* (1999) collected four genotypes of *Lotus corniculatus* near Paris and grew them in controlled environment chambers kept at atmospheric CO<sub>2</sub> concentrations of 350 and 700 ppm. Larvae of the Common Blue Butterfly (*Polyommatus icarus*) that were allowed to feed upon the foliage produced in the CO<sub>2</sub>-enriched air ate more, grew larger and experienced shorter development times than larvae feeding on the foliage produced in the ambient-air treatment, suggesting that this butterfly species will likely become ever more robust and plentiful as the air's CO<sub>2</sub> content continues to rise.

Brooks and Whittaker (1999) removed grassland monoliths containing eggs of the xylem-feeding spittlebug *Neophilaenus lineatus* from the UK's Great Dun Fell in Cumbria and placed them in glasshouses maintained at atmospheric CO<sub>2</sub> concentrations of 350 and 600 ppm for two years. Survival of the spittlebug's nymphal states was reduced by 24% in both of the generations produced in their experiment, suggesting that this particular insect will likely cause less tissue damage to the plants of this species-poor grassland in a CO<sub>2</sub>-enriched world of the future.

Joutei *et al.* (2000) grew bean (*Phaseolus vulgaris*) plants in controlled environments kept at atmospheric CO<sub>2</sub> concentrations of 350 and 700 ppm, to which they introduced the destructive agricultural mite *Tetranychus urticae*, observing that female mites produced 34% and 49% less offspring in the CO<sub>2</sub>-enriched chambers in their first and second generations, respectively. This CO<sub>2</sub>-induced reduction in the reproductive success of this invasive insect, *which negatively affects more than 150 crop species worldwide*, bodes well for mankind's ability to grow the food we will need to feed our growing numbers in the years ahead.

In a somewhat different experiment, Peters *et al.* (2000) fed foliage derived from FACE plots of calcareous grasslands of Switzerland (maintained at 350 and 650 ppm CO<sub>2</sub>) to terrestrial slugs, finding they exhibited no preference with respect to the CO<sub>2</sub> treatment from which the foliage was derived. Also, in a study that targeted no specific insect pest, Castells *et al.* (2002) found

that a doubling of the air's CO<sub>2</sub> content enhanced the total phenolic concentrations of two Mediterranean perennial grasses (*Dactylis glomerata* and *Bromus erectus*) by 15% and 87%, respectively, which compounds tend to enhance plant defensive and resistance mechanisms to attacks by both herbivores and pathogens.

Finally, within a still more different context, Coviella and Trumbel (2000) determined that toxins produced by *Bacillus thuringiensis* (Bt), which are applied to crop plants by spraying as a means of combating various crop pests, were "more efficacious" in cotton grown in an elevated CO<sub>2</sub> environment than in ambient air, which is a big plus for modern agriculture. In addition, Coviella *et al.* (2000) determined that "elevated CO<sub>2</sub> appears to eliminate differences between transgenic [Bt-containing] and nontransgenic plants for some key insect developmental/fitness variables including length of the larval stage and pupal weight," which could prove to be a big plus for nature in the event of inadvertent Bt gene transference to wild relatives of transgenic crop lines.

In summary, the majority of evidence that has been accumulated to date suggests that rising atmospheric CO<sub>2</sub> concentrations may reduce the frequency and severity of pest outbreaks that are detrimental to agriculture, while not seriously impacting herbivorous organisms found in natural ecosystems that are normally viewed in a more favorable light.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/h/herbivoresherbplants.php>.

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### 6.3.2.2. Woody Plants

#### 6.3.2.2.1. MAPLE

Working with *Acer rubrum* saplings beginning their fourth year of growth in open-top chambers maintained at four different atmospheric CO<sub>2</sub>/temperature conditions - (1) ambient temperature, ambient CO<sub>2</sub>, (2) ambient temperature, elevated CO<sub>2</sub> (ambient + 300 ppm), (3) elevated temperature (ambient + 3.5°C), ambient CO<sub>2</sub>, and (4) elevated temperature, elevated CO<sub>2</sub> - Williams *et al.* (2003) bagged first instar gypsy moth larvae on various branches of the trees and observed their behavior. The data they obtained demonstrated, in their words, "that larvae feeding on CO<sub>2</sub>-enriched foliage ate a comparably poorer food source than those feeding on ambient CO<sub>2</sub>-grown plants, irrespective of temperature," and that there was a minor reduction in leaf water content due to CO<sub>2</sub> enrichment. Nevertheless, they found the "CO<sub>2</sub>-induced reductions in foliage quality (e.g. nitrogen and water) were *unrelated* [our italics] to insect mortality, development rate and pupal weight," and that these and any other phytochemical changes that may have occurred "resulted in *no negative effects* [our italics] on gypsy moth performance." They also found that "irrespective of CO<sub>2</sub> concentration, on average, male larvae pupated 7.5 days earlier and female larvae 8 days earlier at elevated temperature," and noting that anything that prolongs the various development stages of insects potentially exposes them to greater predation and parasitism risk, they concluded that the observed temperature-induced hastening of the insects' development would likely expose them to *less* predation and parasitism risk, which would appear to confer an *advantage* upon this particular herbivore in this particular situation.

One year later, Hamilton *et al.* (2004) began the report of their study of this important subject by noting that many single-species investigations have suggested that increases in atmospheric CO<sub>2</sub> will increase herbivory (Bezemer and Jones, 1998; Cannon, 1998; Coviella and Trumble, 1999; Hunter, 2001; Lincoln *et al.*, 1993; Whittaker, 1999). However, because there are so many feedbacks and complex interactions among the numerous components of real-world ecosystems, they warned that one ought not put too much faith in these predictions until relevant real-world ecosystem-level experiments have been completed.

In one such study they conducted at the Duke Forest FACE facility near Chapel Hill, North Carolina, USA, Hamilton *et al.* "measured the amount of leaf tissue damaged by insects and other herbivorous arthropods during two growing seasons in a deciduous forest understory continuously exposed to ambient (360 ppm) and elevated ( 560 ppm) CO<sub>2</sub> conditions." This forest is dominated by loblolly pine trees that account for fully 92% of the ecosystem's total woody biomass. In addition, it contains 48 species of other woody plants (trees, shrubs and vines) that have naturally established themselves in the forest's understory. In their study of this ecosystem, Hamilton *et al.* quantified the loss of foliage due to herbivory that was experienced by three deciduous tree species, one of which was *Acer rubrum*.

So what did they find? As Hamilton *et al.* describe it, "we found that elevated CO<sub>2</sub> led to a trend toward *reduced herbivory* [our italics] in [the] deciduous understory in a situation that included the full complement of naturally occurring plant and insect species." In 1999, for example, they determined that "elevated CO<sub>2</sub> reduced overall herbivory by more than 40%," while in 2000 they say they observed "the same pattern and magnitude of reduction."

With respect to changes in foliage properties that might have been expected to lead to increases in herbivory, Hamilton *et al.* report they "found no evidence for significant changes in leaf nitrogen, C/N ratio, sugar, starch or total leaf phenolics in either year of [the] study," noting that these findings agree with those of "another study performed at the Duke Forest FACE site that also found no effect of elevated CO<sub>2</sub> on the chemical composition of leaves of understory trees (Finzi and Schlesinger, 2002)."

Hamilton *et al.* thus concluded their landmark paper by emphasizing that "despite the large number of studies that predict increased herbivory, particularly from leaf chewers, under elevated CO<sub>2</sub>, our study found a trend toward reduced herbivory two years in a row." In addition, they note that their real-world results "agree with the only other large-scale field experiment that quantified herbivory for a community exposed to elevated CO<sub>2</sub> (Stilling *et al.*, 2003)."

Consequently, and in spite of all of the predictions of increased destruction of natural ecosystems by insects and other herbivorous arthropods in a CO<sub>2</sub>-enriched world of the future, just the *opposite* would appear to be the more likely outcome, i.e., greater plant productivity plus less foliage consumption by herbivores, "whether expressed on an absolute or a percent basis," as Hamilton *et al.* found to be the case in their study.

In another study conducted at the same site, Knepp *et al.* (2005) quantified leaf damage by chewing insects on saplings of seven species (including *Acer rubrum*) in 2001, 2002 and 2003, while five additional species (including *Acer barbatum*) were included in 2001 and 2003. This work revealed, in their words, that "across the seven species that were measured in each of the three years, elevated CO<sub>2</sub> caused a reduction in the percentage of leaf area removed by chewing insects," which was such that "the percentage of leaf tissue damaged by insect herbivores was 3.8% per leaf under ambient CO<sub>2</sub> and 3.3% per leaf under elevated CO<sub>2</sub>." Greatest effects were observed in 2001, when they report that "across 12 species the average

damage per leaf under ambient CO<sub>2</sub> was 3.1% compared with 1.7% for plants under elevated CO<sub>2</sub>," which was "indicative of a 46% decrease in the total area and total mass of leaf tissue damaged by chewing insects in the elevated CO<sub>2</sub> plots."

What was responsible for these welcome results? Knepp *et al.* say that "given the consistent reduction in herbivory under high CO<sub>2</sub> across species in 2001, it appears that some universal feature of chemistry or structure that affected leaf suitability was altered by the treatment." Another possibility they discuss is that "forest herbivory may decrease under elevated CO<sub>2</sub> because of a decline in the abundance of chewing insects," citing the observations of Stiling *et al.* (2002) to this effect and noting that "slower rates of development under elevated CO<sub>2</sub> prolongs the time that insect herbivores are susceptible to natural enemies, which may be abundant in open-top chambers and FACE experiments but absent from greenhouse experiments." In addition, they suggest that "decreased foliar quality and increased per capita consumption under elevated CO<sub>2</sub> may increase exposure to toxins and insect mortality," also noting that "CO<sub>2</sub>-induced changes in host plant quality directly decrease insect fecundity," citing the work of Coviella and Trumble (1999) and Awmack and Leather (2002).

So what's the bottom line with respect to the outlook for earth's forests, and especially its maple trees, in a high-CO<sub>2</sub> world of the future? In their concluding paragraph, Knepp *et al.* say that "in contrast to the view that herbivore damage will increase under elevated CO<sub>2</sub> as a result of compensatory feeding on lower quality foliage, our results and those of Stiling *et al.* (2002) and Hamilton *et al.* (2004) in open experimental systems suggest that damage to trees may decrease."

But what if herbivore-induced damage happens to *increase* - for some strange reason in some situations - in a future CO<sub>2</sub>-enriched world?

The likely answer is provided by the work of Kruger *et al.* (1998), who grew well-watered and fertilized one-year-old *Acer saccharum* saplings in glasshouses maintained at atmospheric CO<sub>2</sub> concentrations of either 356 or 645 ppm for 70 days to determine the effects of elevated CO<sub>2</sub> on photosynthesis and growth. In addition, on the 49th day of differential CO<sub>2</sub> exposure, 50% of the saplings' leaf area was removed from half of the trees in order to study the impact of concomitant *simulated herbivory*. This protocol revealed that the 70-day CO<sub>2</sub> enrichment treatment increased the total dry weight of the non-defoliated seedlings by about 10%. When the trees were stressed by simulated herbivory, however, the CO<sub>2</sub>-enriched maples produced 28% more dry weight over the final phase of the study than the maples in the ambient-air treatment did. This result thus led Kruger *et al.* to conclude that in a high-CO<sub>2</sub> world of the future "sugar maple might be more capable of tolerating severe defoliation events which in the past have been implicated in widespread maple declines."

All in all, therefore, it would appear that earth's maple trees - and probably many, if not most, other trees - may fare much better in the future with respect to the periodic assaults of leaf-damaging herbivores, as the air's CO<sub>2</sub> content continues its upward climb.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/h/herbivoresmaple.php>.

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#### 6.3.2.2.2. OAK

Dury *et al.* (1998) grew four-year-old *Quercus robur* seedlings in pots in greenhouses maintained at ambient and twice-ambient atmospheric CO<sub>2</sub> concentrations in combination with ambient and elevated (ambient plus 3°C) air temperatures for approximately one year to study the interactive effects of elevated CO<sub>2</sub> and temperature on leaf nutritional quality. In doing so, they found that the elevated air temperature treatment significantly reduced leaf palatability, and that leaf toughness increased as a consequence of temperature-induced increases in condensed tannin concentrations. In addition, the higher temperatures significantly reduced leaf nitrogen content, while elevated CO<sub>2</sub> caused a temporary increase in leaf phenolic concentrations and a decrease in leaf nitrogen content.

In one of the first attempts to move outside the laboratory/greenhouse and study the effects of atmospheric CO<sub>2</sub> enrichment on trophic food webs in a natural ecosystem, Stiling *et al.* (1999) enclosed portions of a native scrub-oak community in Florida (USA) within 3.6-m-diameter open-top chambers and fumigated them with air having CO<sub>2</sub> concentrations of either 350 or 700 ppm for approximately one year, in order to see if elevated CO<sub>2</sub> would impact leaf miner densities, feeding rates and mortality in this nutrient-poor ecosystem.

Adherence to this protocol led to the finding that total leaf miner densities were 38% less on the foliage of trees growing in CO<sub>2</sub>-enriched air than on the foliage of trees growing in ambient air. In addition, atmospheric CO<sub>2</sub> enrichment consistently reduced the absolute numbers of the study's six leaf miner species. At the same time, however, the elevated CO<sub>2</sub> treatment increased the leaf area consumed by the *less abundant* herbivore miners by approximately 40% relative to the areas mined by the *more abundant* herbivores present on the foliage exposed to ambient air; but in spite of this increase in feeding, the leaf miners in the CO<sub>2</sub>-enriched chambers experienced significantly greater mortality than those in the ambient-air chambers. Although CO<sub>2</sub>-induced reductions in leaf nitrogen content played a minor role in this phenomenon, the greatest factor contributing to increased herbivore mortality was *a four-fold increase in parasitization by various wasps*, which could more readily detect the more-exposed leaf miners on the CO<sub>2</sub>-enriched foliage.

If extended to agricultural ecosystems, these findings suggest that crops may experience less damage from such herbivores in a high-CO<sub>2</sub> world of the future, thus increasing potential harvest and economic gains. In addition, with reduced numbers of leaf miners in CO<sub>2</sub>-enriched air, farmers could reduce their dependency upon chemical pesticides to control them, thus reducing the negative impacts of these agricultural chemicals on the environment.

In another study conducted on five scrub-oak forest species at the same experimental facility, Stiling *et al.* (2002b) investigated the effects of an approximate doubling of the air's CO<sub>2</sub> concentration on a number of characteristics of several insect herbivores. As before, they found that the "relative levels of damage by the two most common herbivore guilds, leaf-mining

moths and leaf-chewers (primarily larval lepidopterans and grasshoppers), were significantly lower in elevated CO<sub>2</sub> than in ambient CO<sub>2</sub>, for all five plant species," *and* they found that "the response to elevated CO<sub>2</sub> was the same across all plant species." In addition, they report that "more host-plant induced mortality was found for all miners on all plants in elevated CO<sub>2</sub> than in ambient CO<sub>2</sub>." These effects were so powerful, in fact, that in addition to the *relative* densities of insect herbivores being reduced in the CO<sub>2</sub>-enriched chambers, and "even though there were more leaves of most plant species in the elevated CO<sub>2</sub> chambers," the *total* densities of leaf miners in the high-CO<sub>2</sub> chambers were also lower for all plant species. Consequently, it would appear that in a high-CO<sub>2</sub> world of the future, many of earth's plants may be able to better withstand the onslaughts of various insect pests that have plagued them in the past. Another intriguing implication of this finding, as Stiling *et al.* note, is that "reductions in herbivore loads in elevated CO<sub>2</sub> could boost plant growth *beyond what might be expected based on pure plant responses to elevated CO<sub>2</sub>* [our italics]," which is a truly exciting observation.

Continuing to investigate the same ecosystem, which is dominated by two species of scrub oak (*Quercus geminata* and *Q. myrtifolia*) that account for more than 90% of the ecosystem's biomass, and focusing on the abundance of a guild of lepidopteran leafminers that attack the leaves of *Q. myrtifolia*, as well as various leaf chewers that also like to munch on this species, Rossi *et al.* (2004) followed 100 marked leaves in *each* of sixteen open-top chambers (half exposed to ambient air and half exposed to air containing an extra 350 ppm of CO<sub>2</sub>) for a total of nine months, after which, in their words, "differences in mean percent of leaves with leafminers and chewed leaves on trees from ambient and elevated chambers were assessed using paired *t*-tests."

In reporting their findings the researchers wrote that "both the abundance of the guild of leafmining lepidopterans and damage caused by leaf chewing insects attacking myrtle oak were depressed in elevated CO<sub>2</sub>." Specifically, they found that leafminer abundance was 44% lower ( $P = 0.096$ ) in the CO<sub>2</sub>-enriched chambers compared to the ambient-air chambers, and that the abundance of leaves suffering chewing damage was 37% lower ( $P = 0.072$ ) in the CO<sub>2</sub>-enriched air. The implications of these findings are rather obvious: myrtle oak trees growing in their natural habitat will likely suffer far less damage from both leaf miners and leaf chewers as the air's CO<sub>2</sub> concentration continues to rise in the years and decades ahead.

Still concentrating on the same ecosystem, where atmospheric enrichment with an extra 350 ppm of CO<sub>2</sub> was begun in May of 1996, Hall *et al.* (2005b) studied the four species that dominate the community and are present in every experimental chamber: the three oaks (*Quercus myrtifolia*, *Q. chapmanii* and *Q. geminata*) plus the nitrogen-fixing legume *Galactia elliotii*. At three-month intervals from May 2001 to May 2003, undamaged leaves were removed from each of these species in all chambers and analyzed for various chemical constituents, while 200 randomly selected leaves of each species in each chamber were scored for the presence of six types of herbivore damage.

Throughout the study there were no significant differences between the CO<sub>2</sub>-enriched and ambient-treatment leaves of any single species in terms of either condensed tannins, hydrolyzable tannins, total phenolics or lignin. However, in all four species together there were *always* greater concentrations of *all four leaf constituents* in the CO<sub>2</sub>-enriched leaves, with across-species mean increases of 6.8% for condensed tannins, 6.1% for hydrolyzable tannins, 5.1% for total phenolics and 4.3% for lignin. In addition, there were large and often significant CO<sub>2</sub>-induced decreases in all leaf damage categories among all species: chewing (-48%,  $P < 0.001$ ), mines (-37%,  $P = 0.001$ ), eye spot gall (-45%,  $P < 0.001$ ), leaf tier (-52%,  $P = 0.012$ ), leaf mite (-23%,  $P = 0.477$ ) and leaf gall (-16%,  $P = 0.480$ ). Hall *et al.* thus concluded that the changes they observed in leaf chemical constituents and herbivore damage "suggest that damage to plants may decline as atmospheric CO<sub>2</sub> levels continue to rise."

In the final study to come out of the Florida scrub-oak ecosystem that we have reviewed, Hall *et al.* (2005a) studied the effects of an extra 350 ppm of CO<sub>2</sub> on litter quality, herbivore activity and their interactions. Over the three years of this experiment (2000, 2001, 2002), they determined that "changes in litter chemistry from year to year were far larger than effects of CO<sub>2</sub> or insect damage, suggesting that these may have only minor effects on litter decomposition." The one exception to this finding, in their words, was that "condensed tannin concentrations increased under elevated CO<sub>2</sub> regardless of species, herbivore damage, or growing season," rising by 11% in 2000, 18% in 2001 and 41% in 2002 as a result of atmospheric CO<sub>2</sub> enrichment, as best we can determine from their bar graphs. Also, the five researchers report that "lepidopteran larvae can exhibit slower growth rates when feeding on elevated CO<sub>2</sub> plants (Fajer *et al.*, 1991) and become more susceptible to pathogens, parasitoids, and predators (Lindroth, 1996; Stiling *et al.*, 1999)," noting further that at their field site, "which hosts the longest continuous study of the effects of elevated CO<sub>2</sub> on insects, herbivore populations decline[d] markedly under elevated CO<sub>2</sub> (Stiling *et al.*, 1999, 2002, 2003; Hall *et al.*, 2005)."

In conclusion, from the evidence accumulated to date with respect to herbivory in oak trees, it would appear that ever less damage will be done to such trees by various insect pests as the air's CO<sub>2</sub> concentration continues to climb ever higher.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/h/herbivoreswoodoak.php>.

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#### 6.3.2.2.3. OTHER

Stiling *et al.* (1999) enclosed portions of a Florida scrub-oak community in open-top chambers and maintained them at atmospheric CO<sub>2</sub> concentrations of 350 and 700 ppm for approximately one year, while they studied the effects of this treatment on destructive leaf miners. Among their many findings, the researchers noted that the individual areas consumed by leaf miners munching on leaves in the CO<sub>2</sub>-enriched chambers were larger than those created by leaf miners dining on leaves in the ambient-air chambers. As a result, there was a *four-fold increase* in parasitization by various wasps that could more readily detect the more-exposed leaf miners on the CO<sub>2</sub>-enriched foliage. Consequently, leaf miners in the elevated CO<sub>2</sub> chambers suffered significantly greater mortality than those in the control chambers.

In a subsequent and much expanded study of the same ecosystem, Stiling *et al.* (2002) investigated several characteristics of a number of insect herbivores found on the five species of plants that accounted for over 98% of the total plant biomass within the chambers. As they describe their results, the "relative levels of damage by the two most common herbivore guilds, leaf-mining moths and leaf-chewers (primarily larval lepidopterans and grasshoppers), were

significantly lower in elevated CO<sub>2</sub> than in ambient CO<sub>2</sub>, for all five plant species." In addition, they report that "more host-plant induced mortality was found for all miners on all plants in elevated CO<sub>2</sub> than in ambient CO<sub>2</sub>." These effects were so powerful, in fact, that in addition to the *relative* densities of insect herbivores being reduced in the CO<sub>2</sub>-enriched chambers, and "even though there were more leaves of most plant species in the elevated CO<sub>2</sub> chambers," the *total* densities of leaf miners in the high-CO<sub>2</sub> chambers were also lower for all plant species.

In another study of oak trees, Dury *et al.* (1998) grew four-year-old *Quercus robur* saplings in pots placed within greenhouses maintained at ambient and twice-ambient atmospheric CO<sub>2</sub> concentrations in combination with ambient and elevated (ambient plus 3°C) air temperatures. Although no herbivores were included in the experiment, the authors determined that elevated CO<sub>2</sub> would "not [be] expected to affect nutritional quality of foliage for spring-feeding larvae." The increase in temperature, however, increased leaf toughness and led them to conclude that insects feeding on such foliage would experience prolonged larval development and reduced growth.

In another study that did not involve herbivores, Gleadow *et al.* (1998) grew eucalyptus seedlings in glasshouses maintained at 400 and 800 ppm CO<sub>2</sub> for a period of six months, observing biomass increases of 98% and 134% in high and low nitrogen treatments, respectively. They also studied a sugar-based compound called *prunasin*, which produces cyanide in response to tissue damage caused by foraging herbivores. Although elevated CO<sub>2</sub> caused no significant change in leaf prunasin content, it was determined that the proportion of nitrogen allocated to prunasin increased by approximately 20% in the CO<sub>2</sub>-enriched saplings, suggestive of a *potential* for increased prunasin production had the saplings been under attack by herbivores.

In a study of *simulated* herbivory, Kruger *et al.* (1998) grew seedlings of one-year-old maple (*Acer saccharum*) and two-year-old aspen (*Populus tremuloides*) in glasshouses with atmospheric CO<sub>2</sub> concentrations of 356 and 645 ppm for 70 days. At the 49-day point of the experiment, half of the leaf area on half of the trees in each treatment was removed. This defoliation caused the final dry weights of both species to decline in the ambient-air glasshouse. In the CO<sub>2</sub>-enriched glasshouse, on the other hand, the defoliated maple trees ended up weighing just as much as the non-defoliated maple trees; while the defoliated aspen trees ended up weighing a little less, but not significantly less, than their non-defoliated counterparts. Hence, atmospheric CO<sub>2</sub> enrichment helped both species to better recover from the debilitating effect of leaf removal, which suggests that these trees may be better able to deal with the physical damage that might be inflicted upon them by herbivores in a future world of higher atmospheric CO<sub>2</sub> concentration.

In another study of mechanical defoliation, Lovelock *et al.* (1999) grew seedlings of the tropical tree *Copaifera aromatica* for 50 days in pots placed within open-top chambers maintained at atmospheric CO<sub>2</sub> concentrations of 390 and 860 ppm. At the 14-day point of the experiment, half of the seedlings in each treatment had about 40% of their total leaf area removed. In this case, none of the defoliated trees of either CO<sub>2</sub> treatment fully recovered from this

manipulation; but at the end of the experiment, the total plant biomass of the defoliated trees in the CO<sub>2</sub>-enriched treatment was 15% greater than that of the defoliated trees in the ambient-CO<sub>2</sub> treatment, again attesting to the benefits of atmospheric CO<sub>2</sub> enrichment in helping trees to deal with herbivory.

Docherty *et al.* (1997) grew beech and sycamore saplings in glasshouses maintained at atmospheric CO<sub>2</sub> concentrations of 350 and 600 ppm, while groups of three sap-feeding aphid species and two sap-feeding leafhopper species were allowed to feed on them. Overall, elevated CO<sub>2</sub> had few significant effects on the performance of the insects, although there was a non-significant tendency for elevated CO<sub>2</sub> to reduce the individual weights and populations sizes of the aphids.

Finally, Hattenschwiler and Schafellner (1999) grew seven-year-old spruce (*Picea abies*) trees at atmospheric CO<sub>2</sub> concentrations of 280, 420 and 560 ppm and various nitrogen deposition treatments for three years, allowing nun moth larvae to feed on current-year needles for a period of 12 days. Larvae placed upon the CO<sub>2</sub>-enriched foliage consumed less needle biomass than larvae placed upon the ambiently-grown foliage, regardless of nitrogen treatment. In fact, this effect was so pronounced that the larvae feeding on needles produced by the CO<sub>2</sub>-enriched trees attained an average final biomass that was only two-thirds of that attained by the larvae that fed on needles produced at 280 ppm CO<sub>2</sub>. Since the nun moth is a deadly defoliator that resides in most parts of Europe and East Asia between 40 and 60°N latitude and is commonly regarded as the coniferous counterpart of its close relative the gypsy moth, which feeds primarily on deciduous trees, the results of this study thus suggest that the ongoing rise in the air's CO<sub>2</sub> content will likely lead to significant reductions in damage to spruce and other coniferous trees by this voracious insect pest in the years and decades ahead.

In light of these several observations, the balance of evidence seems to suggest that earth's woody plants will be better able to deal with the challenges provided by herbivorous insects as the air's CO<sub>2</sub> content continues to rise.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/h/herbivoreswoodyplants.php>.

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### 6.3.3. Insects

As the atmosphere's CO<sub>2</sub> concentration climbs ever higher, it is important to determine how this phenomenon will affect the delicate balance that exists between earth's plants and the insects that feed on them. In this section we thus review what has been learned about this subject with respect to aphids, moths and other insects.

Additional information on this topic, including reviews on insects not discussed here, can be found at [http://www.co2science.org/subject/i/subject\\_i.php](http://www.co2science.org/subject/i/subject_i.php) under the heading Insects.

#### 6.3.3.1. Aphids

Docherty *et al.* (1997) grew beech and sycamore saplings in glasshouses maintained at atmospheric CO<sub>2</sub> concentrations of 350 and 600 ppm, while groups of three sap-feeding aphid species were allowed to feed on the saplings. Overall, the elevated CO<sub>2</sub> had few significant effects on aphid feeding and performance. There was, however, a non-significant tendency for elevated CO<sub>2</sub> to reduce the individual weights and population sizes of the aphids, suggesting that future increases in the air's CO<sub>2</sub> content *might* reduce aphid feeding pressures on beech and sycamore saplings, and possibly other plants as well.

Whittaker (1999) reviewed the scientific literature dealing with population responses of herbivorous insects to atmospheric CO<sub>2</sub> enrichment, concentrating on papers resulting from relatively long-term studies. Based on all pertinent research reports available at that time, the only herbivorous insects that exhibited population increases in response to elevated CO<sub>2</sub> exposure were those classified as phloem feeders, specifically, aphids. Although this finding

appeared to tip the scales in favor of aphids over plants, additional studies would complicate the issue and swing the pendulum back the other way.

Newman *et al.* (1999) grew tall fescue plants for two weeks in open-top chambers maintained at atmospheric CO<sub>2</sub> concentrations of 350 and 700 ppm before inoculating them with aphids (*Rhopalosiphum padi*). After nine additional weeks of differential CO<sub>2</sub> exposure, the plants were harvested and their associated aphids counted. Although elevated CO<sub>2</sub> increased plant dry matter production by 37%, this phenomenon did *not* result in similar increases in aphid colonization. In fact, the plants grown in air of elevated CO<sub>2</sub> concentration contained *far* fewer aphids than the plants grown in ambient air.

Percy *et al.* (2002) grew the most widely distributed tree species in all of North America - trembling aspen - in twelve 30-m-diameter FACE rings in air maintained at (1) ambient CO<sub>2</sub> and O<sub>3</sub> concentrations, (2) ambient O<sub>3</sub> and elevated CO<sub>2</sub> (560 ppm during daylight hours), (3) ambient CO<sub>2</sub> and elevated O<sub>3</sub> (46.4-55.5 ppb during daylight hours), and (4) elevated CO<sub>2</sub> and O<sub>3</sub> over each growing season from 1998 through 2001. Throughout their experiment they assessed a number of the young trees' growth characteristics, as well as the responses of the sap-feeding aphid *Chaitophorus stevensis*, which they say "infests aspen throughout its range." This experiment revealed that, by itself, elevated CO<sub>2</sub> did not affect aphid abundance; but it increased the densities of natural enemies of the aphids, which over the long term would tend to reduce aphid numbers. Also, by itself, elevated O<sub>3</sub> did not affect aphid abundance, but it had a strong negative effect on natural enemies of aphids, which over the long term would tend to increase aphid numbers. When both trace gases were applied together, however, elevated CO<sub>2</sub> *completely counteracted* the reduction in the abundance of natural enemies of aphids caused by elevated O<sub>3</sub>. Hence, elevated CO<sub>2</sub> tended to reduce the negative impact of aphids on trembling aspen in this comprehensive study.

At about the same time, Holopainen (2002) reviewed the scientific literature dealing with this phenomenon, i.e., the joint effects of elevated concentrations of atmospheric O<sub>3</sub> and CO<sub>2</sub> on aphid-plant interactions. After compiling the results of 26 pertinent studies, it was found that atmospheric CO<sub>2</sub> enrichment increased aphid performance in six studies, decreased it in six studies, and had no significant impact on it in the remaining 14 studies, while similar results were found for aphid-plant interactions in the presence of elevated O<sub>3</sub> concentrations.

Newman (2003) reviewed what was known, and *not* known, about aphid responses to concurrent increases in atmospheric CO<sub>2</sub> and air temperature, while also investigating the subject via the aphid population model of Newman *et al.* (2003). This literature review and model analysis lead him to conclude that when the air's CO<sub>2</sub> concentration and temperature are both elevated, "aphid population dynamics will be more similar to current ambient conditions than expected from the results of experiments studying either factor alone." And if that sounds ambiguous, *it is*. We can only draw the general conclusion, according to Newman, that "insect responses to CO<sub>2</sub> are *unlikely* to all be in the same direction." Nevertheless, he says that "the lack of a simple common phenomenon does not deny that there is some overriding generality



in the responses by the system." It's just that we did not at that time know what that overriding generality was, which is why experimental work on the subject has continued apace.

Concentrating on thermal effects alone, Ma *et al.* (2004) conducted detailed experiments on the impacts of high temperature, period of exposure, and developmental stage on the survival of the aphid *Metopolophium dirhodum*, which they say "is the most abundant of the three cereal aphid species in Germany and central European countries." This protocol revealed, in their words, that "temperatures over 29°C for 8 hours significantly reduced survival, which decreased generally as the temperature increased." They also determined that "exposing aphids to 32.5°C for 4 hours or longer significantly reduced survival," and that "mature aphids had a lower tolerance of high temperatures than nymphs." In light of what they observed, therefore, as well as what a number of other scientists had observed, Ma *et al.* concluded that "global warming may play a role in the long-term changes in the population abundance of *M. dirhodum*." Specifically, they say that "an increase in TX [daily average temperature] of 1°C and MaxT [maximum daily temperature] of 1.3°C during the main period of the aphid population increase would result in a 33% reduction in peak population size," while "an increase in TX of 2°C and MaxT of 2.6°C would result in an early population collapse (74% reduction of population size)." Consequently, it would appear that a little global warming could greatly decrease aphid infestations of cereal crops grown throughout Germany and Central Europe.

Returning to the subject of joint CO<sub>2</sub> and O<sub>3</sub> effects on aphids, Awmack *et al.* (2004) conducted a two-year study at the Aspen FACE site near Rhinelander, Wisconsin, USA, of the individual and combined effects of elevated CO<sub>2</sub> (+200 ppm) and O<sub>3</sub> (1.5 x ambient) on the performance of *Cepegillettea betulaefoliae* aphids feeding on paper birch trees in what they call "the first investigation of the long-term effects of elevated CO<sub>2</sub> and O<sub>3</sub> atmospheres on natural insect herbivore populations." At the individual scale, they report that "elevated CO<sub>2</sub> and O<sub>3</sub> did not significantly affect [aphid] growth rates, potential fecundity (embryo number) or offspring quality." At the population scale, on the other hand, they found that "elevated O<sub>3</sub> had a strong positive effect," but that "elevated CO<sub>2</sub> did not significantly affect aphid populations."

In comparing their results with those of prior related studies, the three scientists report that "the responses of other aphid species to elevated CO<sub>2</sub> or O<sub>3</sub> are also complex." In particular, they note that "tree-feeding aphids show few significant responses to elevated CO<sub>2</sub> (Docherty *et al.*, 1997), while crop-feeding species may respond positively (Awmack *et al.*, 1997; Bezemer *et al.*, 1998; Hughes and Bazzaz, 2001; Zhang *et al.*, 2001; Stacey and Fellowes, 2002), negatively (Newman *et al.*, 1999) or not at all (Hughes and Bazzaz, 2001), and the same species may show different responses on different host plant species (Awmack *et al.*, 1997; Bezemer *et al.*, 1999)." In summarizing their observations, they thus stated that "aphid individual performance did not predict population responses to CO<sub>2</sub> and O<sub>3</sub>," and they concluded that "elevated CO<sub>2</sub> and O<sub>3</sub> atmospheres are unlikely to affect *C. betulaefoliae* populations in the presence of natural enemy communities."

In a study of a different aphid (*Chaitophorus stevensis*) conducted at the same FACE site, Mondor *et al.* (2004) focused on the subject of *pheromones*, which they say "are utilized by

insects for several purposes, including alarm signaling," and which in the case of phloem-feeding aphids induces high-density groups of them on exposed leaves of trembling aspen trees to disperse and move to areas of lower predation risk. In this experiment the four treatments were: control (367 ppm CO<sub>2</sub>, 38 ppb O<sub>3</sub>), elevated CO<sub>2</sub> (537 ppm), elevated O<sub>3</sub> (51 ppb), and elevated CO<sub>2</sub> and O<sub>3</sub> (537 ppm CO<sub>2</sub>, 51 ppb O<sub>3</sub>). Within each treatment, several aspen leaves containing a single aphid colony of 25 ± 2 individuals were treated in one of two different ways: (1) an aphid was prodded lightly on the thorax so as to *not* produce a visible pheromone droplet, or (2) an aphid was prodded more heavily on the thorax and induced to emit a visible pheromone droplet, after which, in the words of the scientists, "aphids exhibiting any dispersal reactions in response to pheromone emission as well as those exhibiting the most extreme dispersal response, walking down the petiole and off the leaf, were recorded over 5 min."

Mondor *et al.*'s observations were striking. They found that the aphids they studied "have diminished escape responses in enriched carbon dioxide environments, while those in enriched ozone have augmented escape responses, to alarm pheromone." In fact, they report that "0% of adults dispersed from the leaf under elevated CO<sub>2</sub>, while 100% dispersed under elevated O<sub>3</sub>," indicating that the effects of elevated CO<sub>2</sub> and elevated O<sub>3</sub> on aphid response to pheromone alarm signaling are diametrically opposed to each other, with elevated O<sub>3</sub> (which is detrimental to vegetation) helping aphids to escape predation and therefore live to do further harm to the leaves they infest, but with elevated CO<sub>2</sub> (which is beneficial to vegetation) making it more difficult for aphids to escape predation and thereby providing yet an additional benefit to plant foliage. Within this context, therefore, ozone may be seen to be *doubly bad* for plants, while carbon dioxide may be seen to be *doubly good*. In addition, Mondor *et al.* state that this phenomenon may be of broader scope than what is revealed by their specific study, noting that other reports suggest that "parasitoids and predators are more abundant and/or efficacious under elevated CO<sub>2</sub> levels (Stiling *et al.*, 1999; Percy *et al.*, 2002), but are negatively affected by elevated O<sub>3</sub> (Gate *et al.*, 1995; Percy *et al.*, 2002)."

In another intriguing study, Chen *et al.* (2004) grew spring wheat from seed to maturity in high-fertility well-watered pots out-of-doors in open-top chambers (OTCs) maintained at atmospheric CO<sub>2</sub> concentrations of 370, 550 and 750 ppm. Approximately two months after seeding, 20 apterous adult aphids (*Sitobion avenae*) from an adjacent field were placed upon the wheat plants of each of 25 pots in each OTC, while 15 pots were left as controls; and at subsequent 5-day intervals, both apterous and alate aphids were counted. Then, about one month later, 10 alate morph fourth instar nymphs were introduced onto the plants of each of nine control pots; and for the next two weeks the number of offspring laid on those plants were recorded and removed daily to measure reproductive activity. Last of all, at the end of the study, the wheat plants were harvested and their various growth responses determined.

Adherence to these protocols revealed that the introduced aphid populations increased after infestation, peaked during the grain-filling stage, and declined a bit as the wheat matured. On the final day of measurement, aphids in the 550-ppm CO<sub>2</sub> treatment were 32% more numerous than those in ambient air, while aphids in the 750-ppm treatment were 50% more numerous. Alate aphids also produced more offspring on host plants grown in elevated CO<sub>2</sub>: 13% more in

the 550-ppm treatment and 19% more in the 750-ppm treatment. As for the wheat plants, Chen *et al.* report that "elevated CO<sub>2</sub> generally enhanced plant height, aboveground biomass, ear length, and number of and dry weight of grains per ear, consistent with most other studies." With respect to aboveground biomass, for example, the 550-ppm treatment displayed an increase of 36%, while the 750-ppm treatment displayed an increase of 50%, in the case of *both* aphid-infested and non-infested plants.

In commenting on their findings, Chen *et al.* report that "aphid infestation caused negative effects on all the plant traits measured ... but the negative effects were smaller than the positive effects of elevated CO<sub>2</sub> on the plant traits." Hence, they concluded that "the increased productivity occurring in plants exposed to higher levels of CO<sub>2</sub> more than compensate for the increased capacity of the aphids to cause damage." In this experiment, therefore, we have a situation where both the plant and the insect that feeds on it were simultaneously benefited by the applied increases in atmospheric CO<sub>2</sub> concentration. In other words, the CO<sub>2</sub>-induced responses resulted in a win-win situation with no loser, as both plant and insect profited.

Last of all, in a study that investigated a number of plant-aphid-predator relationships, Chen *et al.* (2005) grew transgenic cotton plants for 30 days in well watered and fertilized sand/vermiculite mixtures in pots set in controlled-environment chambers maintained at atmospheric CO<sub>2</sub> concentrations of 370, 700 and 1050 ppm. A subset of aphid-infected plants was additionally supplied with predatory ladybugs, while three generations of cotton aphids (*Aphis gossypii*) were subsequently allowed to feed on some of the plants. Based on measurements made throughout this complex set of operations, Chen *et al.* found that (1) "plant height, biomass, leaf area, and carbon:nitrogen ratios were significantly higher in plants exposed to elevated CO<sub>2</sub> levels," (2) "more dry matter and fat content and less soluble protein were found in *A. gossypii* in elevated CO<sub>2</sub>," (3) "cotton aphid fecundity significantly increased ... through successive generations reared on plants grown under elevated CO<sub>2</sub>," (4) "significantly higher mean relative growth rates were observed in lady beetle larvae under elevated CO<sub>2</sub>," and (5) "the larval and pupal durations of the lady beetle were significantly shorter and [their] consumption rates increased when fed *A. gossypii* from elevated CO<sub>2</sub> treatments." In commenting on the significance of their findings, Chen *et al.* say their study "provides the first empirical evidence that changes in prey quality mediated by elevated CO<sub>2</sub> can alter the prey preference of their natural enemies," and in this particular case, they found that this phenomenon could "enhance the biological control of aphids by lady beetle."

In considering the totality of these many experimental findings, it would appear that the ongoing rise in the air's CO<sub>2</sub> content will likely not have a *major* impact, one way or the other, on aphid-plant interactions, although the scales do appear to be slightly tipped in favor of plants over aphids. Yet a third possibility is that both plants *and* aphids will be benefited by atmospheric CO<sub>2</sub> enrichment, but with plants benefiting more.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/i/insectsaphids.php>.

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### 6.3.3.2. Moths

Kerslake *et al.* (1998) collected five-year-old heather plants from a Scottish moor and grew them in open-top chambers maintained at atmospheric CO<sub>2</sub> concentrations of 350 and 600 ppm for 20 months, with and without soil nitrogen fertilization, while at two different times during the study larvae of *Operophtera brumata*, a voracious winter moth whose outbreaks have caused extensive damage to heather moorland in recent years, were allowed to feed upon current-year shoots for up to one month. The results obtained from this experiment revealed that the survivorship of larvae placed on CO<sub>2</sub>-enriched foliage was not significantly different from that of larvae placed on foliage produced in ambient air, regardless of nitrogen treatment. In addition, feeding upon CO<sub>2</sub>-enriched foliage did not affect larval growth rate, development or final pupal weight. Consequently, Kerslake *et al.* state that their study "provides no evidence that increasing atmospheric CO<sub>2</sub> concentrations will affect the potential for outbreak of *Operophtera brumata* on this host."

Hattenschwiler and Schafellner (1999) grew seven-year-old spruce trees at atmospheric CO<sub>2</sub> concentrations of 280, 420 and 560 ppm and in various nitrogen deposition treatments for three years, after which they performed needle quality assessments and allowed nun moth (*Lymantria monacha*) larvae to feed upon current-year needles for twelve days. This moth is an

especially voracious defoliator that resides in most parts of Europe and East Asia between 40 and 60° N latitude, and it is commonly regarded as the "coniferous counterpart" of its close relative the gypsy moth, which feeds primarily upon deciduous trees.

The two scientists determined from their observations that elevated CO<sub>2</sub> significantly enhanced needle starch, tannin and phenolic concentrations, while significantly decreasing needle water and nitrogen contents. Thus, atmospheric CO<sub>2</sub> enrichment reduced overall needle quality from the perspective of this foliage-consuming moth, as nitrogen content is the primary factor associated with leaf quality. Increasing nitrogen deposition, on the other hand, tended to enhance needle quality, for it lowered starch, tannin and phenolic concentrations while boosting needle nitrogen content. Nevertheless, the positive influence of nitrogen deposition on needle quality was not large enough to completely offset the quality reduction caused by elevated CO<sub>2</sub>.

In light of these observations, it was no surprise that larvae placed on CO<sub>2</sub>-enriched foliage consumed less needle biomass than larvae placed on low-CO<sub>2</sub>-grown foliage, regardless of nitrogen treatment, and that the larvae feeding on CO<sub>2</sub>-enriched foliage exhibited reduced relative growth rates and attained an average biomass that was only two-thirds of that attained by larvae consuming foliage produced at 280 ppm CO<sub>2</sub>. As a result, Hattenschwiler and Schafellner state that "altered needle quality in response to elevated CO<sub>2</sub> will impair the growth and development of *Lymantria monacha* larvae," which should lead to reductions in the degree of spruce tree destruction caused by this voracious defoliator.

Stiling *et al.* (2002) studied the effects of an approximate doubling of the air's CO<sub>2</sub> concentration on a number of characteristics of several insect herbivores feeding on plants native to a scrub-oak forest ecosystem at the Kennedy Space Center, Florida, USA, in eight ambient and eight CO<sub>2</sub>-enriched open-top chambers. In describing their findings, they say that the "relative levels of damage by the two most common herbivore guilds, leaf-mining moths and leaf-chewers (primarily larval lepidopterans and grasshoppers), were significantly lower in elevated CO<sub>2</sub> than in ambient CO<sub>2</sub>," and that "the response to elevated CO<sub>2</sub> was the same across all plant species." Also, they report that "more host-plant induced mortality was found for all miners on all plants in elevated CO<sub>2</sub> than in ambient CO<sub>2</sub>." These effects were so powerful, in fact, that in addition to the *relative* densities of insect herbivores being reduced in the CO<sub>2</sub>-enriched chambers, and "even though there were more leaves of most plant species in the elevated CO<sub>2</sub> chambers," the *total* densities of leaf miners in the high-CO<sub>2</sub> chambers were also lower for all plant species. Hence, it would appear that in a higher CO<sub>2</sub> world of the future, earth's natural ecosystems may well be able to better withstand the onslaughts of various insect pests, including moths, that have plagued them in years and ages past. An interesting implication of this finding, as Stiling *et al.* note, is that "reductions in herbivore loads in elevated CO<sub>2</sub> could boost plant growth *beyond what might be expected based on pure plant responses to elevated CO<sub>2</sub>* [our italics]," which is a truly exciting observation.

Williams *et al.* (2003) bagged first instar gypsy moth larvae on branches of red maple saplings that were entering their fourth year of growth within open-top chambers that were maintained

at four sets of CO<sub>2</sub>/temperature conditions: (1) ambient temperature, ambient CO<sub>2</sub>, (2) ambient temperature, elevated CO<sub>2</sub> (ambient + 300 ppm), (3) elevated temperature (ambient + 3.5°C), ambient CO<sub>2</sub>, and (4) elevated temperature, elevated CO<sub>2</sub>. Under these conditions they measured several parameters that were required to test their hypothesis that a CO<sub>2</sub>-enriched atmosphere would lead to reductions in foliar nitrogen concentrations and increases in defensive phenolics that would in turn lead to increases in insect mortality. The results they obtained indicated, in their words, "that larvae feeding on CO<sub>2</sub>-enriched foliage ate a comparably poorer food source than those feeding on ambient CO<sub>2</sub>-grown plants, irrespective of temperature." Nevertheless, they determined that "CO<sub>2</sub>-induced reductions in foliage quality were unrelated to insect mortality, development rate and pupal weight." As a result, they were forced to conclude that "phytochemical changes resulted in no negative effects on gypsy moth performance," but neither did they help them, which is good.

Because increases in the air's CO<sub>2</sub> concentration typically lead to greater decreases in the concentrations of nitrogen in the foliage of C<sub>3</sub> as opposed to C<sub>4</sub> grasses, Barbehenn *et al.* (2004) say "it has been predicted that insect herbivores will increase their feeding damage on C<sub>3</sub> plants to a greater extent than on C<sub>4</sub> plants (Lincoln *et al.*, 1984, 1986; Lambers, 1993). To test this hypothesis, they thus grew *Lolium multiflorum* (Italian ryegrass, a common C<sub>3</sub> pasture grass) and *Bouteloua curtipendula* (sideoats gramma, a native C<sub>4</sub> rangeland grass) in chambers maintained at either the ambient atmospheric CO<sub>2</sub> concentration of 370 ppm or the doubled CO<sub>2</sub> concentration of 740 ppm for two months, after which newly-molted sixth-instar larvae of *Pseudaletia unipuncta* (a grass-specialist noctuid) and *Spodoptera frugiperda* (a generalist noctuid) were allowed to feed upon the grasses' foliage.

As expected, Barbehenn *et al.* found that foliage protein concentration decreased by 20% in the C<sub>3</sub> grass, but by only 1% in the C<sub>4</sub> grass, when they were grown in CO<sub>2</sub>-enriched air; and they say that "to the extent that protein is the most limiting of the macronutrients examined, these changes represent a decline in the nutritional quality of the C<sub>3</sub> grass." However, and "contrary to our expectations," in the words of Barbehenn *et al.*, "neither caterpillar species significantly increased its consumption rate to compensate for the lower concentration of protein in [the] C<sub>3</sub> grass," and they note that "this result does not support the hypothesis that C<sub>3</sub> plants will be subject to greater rates of herbivory relative to C<sub>4</sub> plants in future [high-CO<sub>2</sub>] atmospheric conditions (Lincoln *et al.*, 1984)." In addition, and "despite significant changes in the nutritional quality of *L. multiflorum* under elevated CO<sub>2</sub>," they note that "no effect on the relative growth rate of either caterpillar species on either grass species resulted," and that there were "no significant differences in insect performance between CO<sub>2</sub> levels." By way of explanation of these results, they suggest that "post-ingestive mechanisms could provide a sufficient means of compensation for the lower nutritional quality of C<sub>3</sub> plants grown under elevated CO<sub>2</sub>."

In light of these observations, and contrary to early simplistic thought on the matter, Barbehenn *et al.* suggest "there will not be a single pattern that characterizes all grass feeders" with respect to their feeding preferences and developmental responses in a world where certain C<sub>3</sub> plants may experience foliar protein concentrations that are lower than those they exhibit today, nor will the various changes that may occur necessarily be detrimental to

herbivore development or to the health and vigor of their host plants. Nevertheless, subsequent studies continue to suggest that various moth species will likely be negatively impacted by the ongoing rise in the air's CO<sub>2</sub> content.

A case in point is the study of Chen *et al.* (2005), who grew well watered and fertilized cotton plants of two varieties (one expressing *Bacillus thuringiensis* toxin genes and one a non-transgenic cultivar from the same recurrent parent) in pots placed within open-top chambers maintained at either 376 or 754 ppm CO<sub>2</sub> in Sanhe County, Hebei Province, China, from planting in mid-May to harvest in October, while immature bolls were periodically collected and analyzed for various chemical characteristics and others were stored under refrigerated conditions for later feeding to larvae of the cotton bollworm. By these means they found that the elevated CO<sub>2</sub> treatment increased immature boll concentrations of condensed tannins by approximately 22% and 26% in transgenic and non-transgenic cotton, respectively, and that it slightly decreased the body biomass of the cotton bollworm and reduced moth fecundity. The Bt treatment was even more effective in this regard; and in the combined Bt-high-CO<sub>2</sub> treatment, the negative cotton bollworm responses were expressed most strongly of all.

Last of all, we report the findings of Rossi *et al.* (2004), who, in a follow-up study to that of Stiling *et al.* that was conducted in the same experimental facilities, focused on the abundance of a guild of lepidopteran leafminers that attack the leaves of myrtle oak, as well as various leaf chewers that also like to munch on this species. Specifically, they periodically examined 100 marked leaves in each of sixteen open-top chambers for a total of nine months, after which, in their words, "differences in mean percent of leaves with leafminers and chewed leaves on trees from ambient and elevated chambers were assessed using paired t-tests." This protocol revealed, in their words, that "both the abundance of the guild of leafmining lepidopterans and damage caused by leaf chewing insects attacking myrtle oak were depressed in elevated CO<sub>2</sub>." Leafminer abundance was 44% lower ( $P = 0.096$ ) in the CO<sub>2</sub>-enriched chambers compared to the ambient-air chambers, while the abundance of leaves suffering chewing damage was 37% lower ( $P = 0.072$ ) in the CO<sub>2</sub>-enriched air.

In conclusion, and considering the results of all of the studies reviewed in this summary, it would appear that the ongoing rise in the air's CO<sub>2</sub> content will *not* result in greater damage to earth's vegetation by the larvae of the many moths that inhabit the planet. If anything, it could well *reduce* the damage they cause.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/i/moths.php>.

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### 6.3.3.3. Other Insects

We have treated the subject on what effect the air's rising CO<sub>2</sub> content might have on the delicate balance that exists between various plants and the insects that feed on them in some detail with respect to aphids and moths in the previous two subsections of this report. Here, we review the results of studies that have reported on other insects.

Docherty *et al.* (1997), in addition to studying aphids, studied two sap-feeding leafhopper species that were allowed to feed on saplings of beech and sycamore that were grown in glasshouses maintained at atmospheric CO<sub>2</sub> concentrations of 350 and 600 ppm. As far as they could determine, there were no significant effects of the extra CO<sub>2</sub> on either the feeding or performance characteristics of either leafhopper species.

In a literature review of more than 30 studies published two years later, Whittaker (1999) found that chewing insects (leaf chewers and leaf miners) showed either no change or actual *reductions* in abundance in response to atmospheric CO<sub>2</sub> enrichment, noting, however, that population reductions in this feeding guild were often accompanied by increased herbivory in response to CO<sub>2</sub>-induced reductions in leaf nitrogen content.

Contemporaneously, Stiling *et al.* (1999) reported the results of what may possibly have been the first attempt to study the effects of elevated CO<sub>2</sub> on trophic webs in a natural ecosystem, specifically, a nutrient-poor scrub-oak community in Florida, USA, where sixteen open-top chambers of 3.6-m diameter were fumigated with air of either 350 or 700 ppm CO<sub>2</sub> for approximately one year. At the end of this period, total leaf miner densities were 38% less on the CO<sub>2</sub>-enriched foliage than on the foliage of the ambiently-grown plants. Moreover, atmospheric CO<sub>2</sub> enrichment consistently reduced the numbers of all six species of leaf miners studied. In a compensatory development, however, exposure to elevated CO<sub>2</sub> increased the amount of leaf area consumed by the less abundant leaf miners by approximately 40%. Nevertheless, leaf miners in the CO<sub>2</sub>-enriched chambers experienced significantly greater mortality than those in the control chambers. Although CO<sub>2</sub>-induced reductions in leaf nitrogen content were determined to have played a minor role in the mortality increase, the greatest factor contributing to this phenomenon was a four-fold increase in parasitization by various wasps that could more readily detect the more-exposed leaf miners on the CO<sub>2</sub>-enriched foliage.

Three years later, Stiling *et al.* (2002) reported even more dramatic effects of the elevated CO<sub>2</sub> of this experiment on leaf chewers. The relative levels of damage by these insects (primarily larval lepidopterans and grasshoppers) were significantly lower in the elevated CO<sub>2</sub> chambers than in the ambient CO<sub>2</sub> chambers for all five of the plant species that accounted for over 98% of the total plant biomass of the ecosystem. In addition, the response to elevated CO<sub>2</sub> was the same across all plant species. Also, they reported that more *host-plant-induced mortality* was found for all miners on all plants in elevated CO<sub>2</sub> than in ambient CO<sub>2</sub>. These effects were so powerful, in fact, that in addition to the *relative* densities of insect herbivores being reduced in the CO<sub>2</sub>-enriched chambers, and even though there were more leaves on most plant species in the elevated CO<sub>2</sub> chambers, the *total* densities of leaf miners in the high-CO<sub>2</sub> chambers were also lower for all plant species. An interesting implication of these findings, as expressed by Stiling *et al.*, is that "reductions in herbivore loads in elevated CO<sub>2</sub> could boost plant growth beyond what might be expected based on pure plant responses to elevated CO<sub>2</sub>," which is truly an exciting thing to contemplate.

In another experiment conducted on a natural ecosystem in Wisconsin, USA -- comprised predominantly of trembling aspen (*Populus tremuloides* Michx.) -- Percy *et al.* (2002) studied the effects of increases in CO<sub>2</sub> alone (to 560 ppm during daylight hours), O<sub>3</sub> alone (to 46.4-55.5 ppb during daylight hours), and CO<sub>2</sub> and O<sub>3</sub> together on the forest tent caterpillar (*Malacosoma disstria*), a common leaf-chewing lepidopteran found in North American hardwood forests. By itself, elevated CO<sub>2</sub> *reduced* caterpillar performance by *reducing* female pupal mass; while elevated O<sub>3</sub> alone *improved* caterpillar performance by *increasing* female pupal mass. When

both gases were applied together, however, the elevated CO<sub>2</sub> *completely counteracted* the enhancement of female pupal mass caused by elevated O<sub>3</sub>. Hence, either alone or in combination with undesirable increases in the air's O<sub>3</sub> concentration, elevated CO<sub>2</sub> tended to reduce the performance of the forest tent caterpillar. This finding is particularly satisfying because, in the words of Percy *et al.*, "historically, the forest tent caterpillar has defoliated more deciduous forest than any other insect in North America," and because "outbreaks can reduce timber yield up to 90% in one year, and increase tree vulnerability to disease and environmental stress."

In a study of yet another type of insect herbivore, Brooks and Whittaker (1999) removed grassland monoliths from the Great Dun Fell of Cumbria, UK -- which contained eggs of a destructive xylem-feeding spittlebug (*Neophilaenus lineatus*) -- and grew them in glasshouses maintained for two years at atmospheric CO<sub>2</sub> concentrations of 350 and 600 ppm. During the course of their experiment, two generations of the xylem-feeding insect were produced; and in each case, elevated CO<sub>2</sub> reduced the survival of nymphal stages by an average of 24%. Brooks and Whittaker suggest that this reduction in survival rate may have been caused by CO<sub>2</sub>-induced reductions in stomatal conductance and transpirational water loss, which may have reduced xylem nutrient-water availability. Whatever the mechanism, the results of this study bode well for the future survival of these species-poor grasslands as the air's CO<sub>2</sub> content continues to rise.

Finally, we report one last study that has nothing to do with CO<sub>2</sub> directly, but with global warming, which climate-alarmists claim is caused by elevated levels of atmospheric CO<sub>2</sub>. In this work of Thomas *et al.* (2001), it is demonstrated that, in response to regional warming in the British Isles over the last two decades of the 20th century, there was an unusually rapid northward expansion of the ranges of two species of cricket: the long-winged cone-head (*Conocephalus discolor*) and Roesel's bush cricket (*Metrioptera roeselii*). The reason for this increased rate of range expansion, according to Thomas *et al.*, resides in the fact that, *in response to the regional warming*, the crickets produced "increased fractions of longer-winged (dispersive) individuals in recently founded populations" that "resulted in about 3- to 15-fold increases in expansion rates, allowing these insects to cross habitat disjunctions that would have represented major or complete barriers to dispersal before the expansions started."

In summing up the implications of the various phenomena described in this section, it would appear that both CO<sub>2</sub>-induced and warming-induced changes in the physical characteristics and behavioral patterns of a diverse assemblage of insect types portend good things for the biosphere in the years and decades to come.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/i/insectsother.php>.

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#### 6.3.4. Interaction of CO<sub>2</sub> and Light on Plant Growth

Is the growth-enhancing effect of atmospheric CO<sub>2</sub> enrichment reduced when light intensities are less than optimal? In a review of the scientific literature designed to answer this question, Kerstiens (1998) analyzed the results of 15 previously published studies of trees having differing degrees of shade tolerance, finding that elevated CO<sub>2</sub> caused greater relative biomass increases in shade-tolerant species than in shade-intolerant or sun-loving species. In fact, in more than half of the studies analyzed, shade-tolerant species experienced CO<sub>2</sub>-induced relative growth increases that were two to three times *greater* than those of less shade-tolerant species.

In an extended follow-up review analyzing 74 observations from 24 studies, Kerstiens (2001) reported that twice-ambient CO<sub>2</sub> concentrations increased the relative growth response of shade-tolerant and shade-intolerant woody species by an average of 51 and 18%, respectively. Moreover, similar results were reported by Poorter and Perez-Soba (2001), who performed a detailed meta-analysis of research results pertaining to this topic, and more recently by Kubiske *et al.* (2002), who measured photosynthetic acclimation in aspen and sugar maple trees. Low light intensity, therefore, is by no means a roadblock to the benefits that come to plants as a consequence of an increase in the air's CO<sub>2</sub> content.

Of course, most general rules do have their exceptions. In one such study, a 200-ppm increase in the air's CO<sub>2</sub> concentration enhanced the photosynthetic rates of sunlit and shaded leaves of sweetgum trees by 92 and 54%, respectively, at one time of year, and by 166 and 68% at another time (Herrick and Thomas, 1999). Likewise, Naumburg and Ellsworth (2000) reported that a 200-ppm increase in the air's CO<sub>2</sub> content boosted steady-state photosynthetic rates in leaves of four hardwood understory species by an average of 60 and 40% under high and low light intensities, respectively. Thus, even though these photosynthetic responses were significantly less in shaded leaves, they were still substantial, with mean increases ranging from 40 to 68% for a 60% increase in atmospheric CO<sub>2</sub> concentration. And that's anything but shabby!

Under *extremely* low light intensities, the benefits arising from atmospheric CO<sub>2</sub> enrichment may be small, but oftentimes they are very important in terms of plant carbon budgeting. In the study of Hattenschwiler (2001), for example, seedlings of five temperate forest species subjected to an additional 200-ppm CO<sub>2</sub> under light intensities that were only 3.4 and 1.3% of full sunlight exhibited CO<sub>2</sub>-induced biomass increases that ranged from 17 to 74%. Similarly, in the study of Naumburg *et al.* (2001), a 200-ppm increase in the air's CO<sub>2</sub> content enhanced photosynthetic carbon uptake in three of four hardwood understory species by more than two-fold in three of the four species under light irradiances that were as low as 3% of full sunlight.

In a final study we have reviewed on our web site, in which potato plantlets inoculated with an arbuscular mycorrhizal fungus were grown at various light intensities and *super* CO<sub>2</sub> enrichment of approximately 10,000 ppm, Louche-Tessandier *et al.* (1999) found that the unusually high CO<sub>2</sub> concentration produced an unusually high degree of root colonization by the beneficial mycorrhizal fungus, which typically helps supply water and nutrients to plants. And it did so irrespective of the degree of light intensity to which the potato plantlets were exposed.

So, whether light intensity is high or low, or leaves are shaded or sunlit, when the CO<sub>2</sub> content of the air is increased, so too are the various biological processes that lead to plant robustness also increased. Less than optimal light intensities, therefore, clearly do *not* negate the beneficial effects of atmospheric CO<sub>2</sub> enrichment.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/g/lightinteraction.php>.

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### 6.3.5. Interaction of CO<sub>2</sub> and O<sub>3</sub> on Plant Growth

Plants grown in CO<sub>2</sub>-enriched air nearly always exhibit increased photosynthetic rates and biomass production relative to plants grown at the current ambient CO<sub>2</sub> concentration. In contrast, plants exposed to elevated ozone concentrations typically display reductions in photosynthesis and growth in comparison with plants grown at the current ambient ozone concentration. Thus, it is important to determine how major plants respond to concomitant increases in the abundances of these two trace gases of the atmosphere, as their concentrations will likely continue to increase for many years to come. We begin with a review of the literature with respect to various agriculture species, followed by a discussion on trees.

Additional information on this topic, including reviews on the interaction of CO<sub>2</sub> and O<sub>3</sub> not discussed here, can be found at [http://www.co2science.org/subject/o/subject\\_o.php](http://www.co2science.org/subject/o/subject_o.php) under the heading Ozone.

#### 6.3.5.1. Agricultural Species

Several studies have used soybean as a model plant to study the effects of elevated CO<sub>2</sub> and ozone on photosynthesis and growth. Reid *et al.* (1998), for example, grew soybeans for an

entire season at different combinations of atmospheric CO<sub>2</sub> and ozone, reporting that elevated CO<sub>2</sub> enhanced rates of photosynthesis in the presence or absence of ozone and that it typically ameliorated the negative effects of elevated ozone on carbon assimilation. At the cellular level, Heagle *et al.* (1998a) reported that at twice the current ambient ozone concentration, soybeans simultaneously exposed to twice the current ambient atmospheric CO<sub>2</sub> concentration exhibited far less foliar injury while maintaining significantly greater leaf chlorophyll contents than control plants exposed to elevated ozone and ambient CO<sub>2</sub> concentrations. By harvest time, these same plants (grown in the elevated ozone/elevated CO<sub>2</sub> treatment combination) had produced 53% more total biomass than their counterparts did at elevated ozone and ambient CO<sub>2</sub> concentrations (Miller *et al.*, 1998). Finally, in analyzing seed yield, it was determined that atmospheric CO<sub>2</sub> enrichment enhanced this parameter by 20% at ambient ozone, while it increased it by 74% at twice the ambient ozone concentration (Heagle *et al.*, 1998b). Thus, elevated CO<sub>2</sub> completely ameliorated the negative effects of elevated ozone concentration on photosynthetic rate and yield production in soybean.

Such ameliorating responses of elevated CO<sub>2</sub> to ozone pollution are not unique to soybeans; they have also been reported for various cultivars of spring and winter wheat. In the study of Tiedemann and Firsching (2000), for example, atmospheric CO<sub>2</sub> enrichment not only overcame the detrimental effects of elevated ozone on photosynthesis and growth, it overcame the deleterious consequences resulting from inoculation with a biotic pathogen as well. Indeed, although infected plants displayed less *absolute* yield than non-infected plants at elevated ozone concentrations, atmospheric CO<sub>2</sub> enrichment caused the greatest *relative* yield increase in *infected* plants (57% vs. 38%).

McKee *et al.* (2000) reported that O<sub>3</sub>-induced reductions in leaf rubisco contents in spring wheat were reversed when plants were simultaneously exposed to twice-ambient concentrations of atmospheric CO<sub>2</sub>. In the study of Vilhena-Cardoso and Barnes (2001), elevated ozone concentrations reduced photosynthetic rates in spring wheat grown at three different soil nitrogen levels. However, when concomitantly exposed to twice-ambient atmospheric CO<sub>2</sub> concentrations, elevated ozone had absolutely no effect on rates of photosynthesis, regardless of soil nitrogen. Going a step further, Pleijel *et al.* (2000) observed that ozone-induced reductions in spring wheat yield were partially offset by concomitant exposure to elevated CO<sub>2</sub> concentrations. Similar results have been reported in spring wheat by Hudak *et al.* (1999) and in winter wheat by Heagle *et al.* (2000).

Other studies have observed similar responses in cotton and potato. Cotton plants grown at elevated ozone concentrations exhibited 25 and 48% reductions in leaf mass per unit area and foliar starch concentration, respectively, relative to control plants grown in ambient air. When simultaneously exposed to twice-ambient CO<sub>2</sub> concentrations, however, the reductions in these parameters were only 5 and 7%, respectively (Booker, 2000). With respect to potato, Wolf and van Oijen (2002) used a validated potato model to predict increases in European tuber production ranging from 1,000 to 3,000 kg of dry matter per hectare in spite of concomitant increases in ozone concentrations and air temperatures.

It is clear from these studies that elevated CO<sub>2</sub> reduces, and nearly always completely overrides, the negative effects of ozone pollution on plant photosynthesis, growth and yield. When explaining the mechanisms behind such responses, most authors suggest that atmospheric CO<sub>2</sub> enrichment tends to reduce stomatal conductance, which causes less indiscriminate uptake of ozone into internal plant air spaces and reduces subsequent conveyance to tissues where damage often results to photosynthetic pigments and proteins, ultimately reducing plant growth and biomass production.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/o/ozoneplantsag.php>.

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### 6.3.5.2. Woody Species

#### 6.3.5.2.1. ASPEN

Karnosky *et al.* (1999) grew O<sub>3</sub>-sensitive and O<sub>3</sub>-tolerant aspen clones in 30-m diameter plots at the Aspen FACE site near Rhinelander, Wisconsin, USA, which were maintained at atmospheric CO<sub>2</sub> concentrations of 360 and 560 ppm with and without exposure to elevated O<sub>3</sub> (1.5 times ambient ozone concentration). After one year of growth at ambient CO<sub>2</sub>, elevated O<sub>3</sub> had caused visible injury to leaves of both types of aspen, with the average percent damage in O<sub>3</sub>-sensitive clones being more than three times as great as that observed in O<sub>3</sub>-tolerant clones (55% vs. 17%, respectively). In combination with elevated CO<sub>2</sub>, however, O<sub>3</sub>-induced damage to leaves of these same clones was only 38% and 3%, respectively. Thus, elevated CO<sub>2</sub> ameliorated much of the foliar damage induced by high O<sub>3</sub> concentrations.

King *et al.* (2001) studied the same plants for a period of two years, concentrating on belowground growth, where elevated O<sub>3</sub> alone had no effect on fine-root biomass. When the two aspen clones were simultaneously exposed to elevated CO<sub>2</sub> and O<sub>3</sub>, however, there was an approximate 66% increase in the fine-root biomass of both of them.

Also in the same experiment, Noormets *et al.* (2001) studied the interactive effects of O<sub>3</sub> and CO<sub>2</sub> on photosynthesis, finding that elevated CO<sub>2</sub> increased rates of photosynthesis in both clones at all leaf positions. Maximum rates of photosynthesis were increased in the O<sub>3</sub>-tolerant clone by averages of 33 and 49% due to elevated CO<sub>2</sub> alone and in combination with elevated O<sub>3</sub>, respectively, while in the O<sub>3</sub>-sensitive clone they were increased by 38% in both situations. Hence, CO<sub>2</sub>-induced increases in maximal rates of net photosynthesis were typically maintained, and sometimes even *increased*, during simultaneous exposure to elevated O<sub>3</sub>.

Yet again in the same experiment, Oksanen *et al.* (2001) reported that after *three* years of treatment, ozone exposure caused significant structural injuries to thylakoid membranes and the stromal compartment within chloroplasts, but that these injuries were largely ameliorated by atmospheric CO<sub>2</sub> enrichment. Likewise, leaf thickness, mesophyll tissue thickness, the amount of chloroplasts per unit cell area, and the amount of starch in leaf chloroplasts were all decreased in the high ozone treatment; but in the case of these leaf properties, simultaneous

exposure of the ozone-stressed trees to elevated CO<sub>2</sub> *more* than compensated for the ozone-induced reductions.

After *four* years of growing *five* aspen clones with varying degrees of tolerance to ozone under the same experimental conditions, McDonald *et al.* (2002) developed what they termed a "competitive stress index," based on the heights of the four nearest neighbors of each tree, to study the influence of competition on the CO<sub>2</sub> growth response of the various clones as modified by ozone. In general, elevated O<sub>3</sub> reduced aspen growth independent of competitive status, while the authors noted an "apparent convergence of competitive performance responses in +CO<sub>2</sub> +O<sub>3</sub> conditions," which they say suggests that "stand diversity may be maintained at a higher level" in such circumstances.

Percy *et al.* (2002) utilized the same experimental setting to assess a number of the trees' growth characteristics, as well as the responses of one plant pathogen and two insects with different feeding strategies that typically attack the trees. Of the plant pathogen studied, they say that "the poplar leaf rust, *Melampsora medusae*, is common on aspen and belongs to the most widely occurring group of foliage diseases." As for the two insects, they report that "the forest tent caterpillar, *Malacosoma disstria*, is a common leaf-chewing lepidopteran in North American hardwood forests" and that "the sap-feeding aphid, *Chaitophorus stevensis*, infests aspen throughout its range." Hence, the rust and the two insect pests the scientists studied are widespread and have significant deleterious impacts on trembling aspen and other tree species. As but one example of this fact, the authors note that, "historically, the forest tent caterpillar has defoliated more deciduous forest than any other insect in North America" and that "outbreaks can reduce timber yield up to 90% in one year, and increase tree vulnerability to disease and environmental stress."

By itself, Percy *et al.* found that elevated O<sub>3</sub> decreased tree height and trunk diameter, increased rust occurrence by nearly fourfold, improved tent caterpillar performance by increasing female pupal mass by 31%, and had a strong negative effect on the natural enemies of aphids. The addition of the extra CO<sub>2</sub>, however, *completely ameliorated* the negative effects of elevated O<sub>3</sub> on tree height and trunk diameter, *reduced* the O<sub>3</sub>-induced enhancement of rust development from nearly fourfold to just over twofold, *completely ameliorated* the enhancement of female tent caterpillar pupal mass caused by elevated O<sub>3</sub>, and *completely ameliorated* the reduction in the abundance of natural enemies of aphids caused by elevated O<sub>3</sub>.

In a final study from the Aspen FACE site, Holton *et al.* (2003) raised parasitized and non-parasitized forest tent caterpillars on two quaking aspen genotypes (O<sub>3</sub>-sensitive and O<sub>3</sub>-tolerant) alone and in combination for one full growing season; and they too found that elevated O<sub>3</sub> improved tent caterpillar performance under ambient CO<sub>2</sub> conditions, *but not in CO<sub>2</sub>-enriched air*.

In summary, it is clear that elevated ozone concentrations have a number of significant negative impacts on the well-being of North America's most widely distributed tree species,

while elevated carbon dioxide concentrations have a number of significant positive impacts. In addition, elevated CO<sub>2</sub> often *completely eliminates* the negative impacts of elevated O<sub>3</sub>. Hence, if the tropospheric O<sub>3</sub> concentration continues to rise as expected (Percy *et al.* note that "damaging O<sub>3</sub> concentrations currently occur over 29% of the world's temperate and subpolar forests but are predicted to affect fully 60% by 2100"), we had better hope that the air's CO<sub>2</sub> content continues to rise as well. If it doesn't, aspen trees will be in a world of hurt; for Percy *et al.* additionally report that "since the mid-1990s, aspen use has increased almost exponentially in the US Great Lakes Region and in the boreal mixed wood region of Canada, where the resource is now almost fully utilized."

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/o/ozoneaspen.php>.

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#### 6.3.5.2.2. BEECH

In discussing the problem of elevated tropospheric ozone (O<sub>3</sub>) concentrations, Liu *et al.* (2004) wrote that "ozone is considered to be one of the air pollutants most detrimental to plant growth and development in both urban and rural environments (Lefohn, 1992; Skarby *et al.*, 1998; Matyssek and Innes, 1999)," because it "reduces the growth and yield of numerous agronomic crops as well as fruit and forest trees (Retzlaff *et al.*, 1997; Fumagalli *et al.*, 2001; Matyssek and Sandermann, 2003)." In addition, they say that ozone concentrations are "currently two to three times higher than in the early 1900s (Galloway, 1998; Fowler *et al.*, 1999)," and that they likely "will remain high in the future (Elvingson, 2001)." Hence, in our quest to determine how the ongoing rise in the atmosphere's CO<sub>2</sub> concentration might impact this unfortunate situation, we here briefly summarize the results of studies that have examined the issue as it pertains to European beech (*Fagus sylvatica* L.) trees.

Liu *et al.* (2005) grew 3- and 4-year-old European beech seedlings for five months in well watered and fertilized soil in containers located within walk-in phytotrons maintained at either ambient or ambient + 300 ppm CO<sub>2</sub> (each subdivided into ambient and double-ambient O<sub>3</sub> concentration treatments, with maximum ozone levels restricted to <150 ppb), in both monoculture and in competition with Norway spruce, after which they examined the effects of each treatment on leaf non-structural carbohydrate levels (soluble sugars and starch). In doing so, they found that the effects of elevated O<sub>3</sub> alone on non-structural carbohydrate levels were small when the beech seedlings were grown in monoculture. When they were grown in mixed culture, however, the elevated O<sub>3</sub> slightly enhanced leaf sugar levels, but reduced starch levels by 50%.

With respect to elevated CO<sub>2</sub> alone, for the beech seedlings grown in both monoculture and mixed culture, levels of sugar and starch were significantly enhanced. Hence, when elevated O<sub>3</sub> and CO<sub>2</sub> significantly affected non-structural carbohydrate levels, elevated CO<sub>2</sub> tended to enhance them, whereas elevated O<sub>3</sub> tended to reduce them. In addition, the combined effects of elevated CO<sub>2</sub> and O<sub>3</sub> acting together were such as to produce a significant increase in leaf non-structural carbohydrates in both mixed and monoculture conditions. As a result, the researchers concluded that "since the responses to the combined exposure were more similar to elevated pCO<sub>2</sub> than to elevated pO<sub>3</sub>, apparently elevated pCO<sub>2</sub> overruled the effects of elevated pO<sub>3</sub> on non-structural carbohydrates."

In a slightly longer study, Grams *et al.* (1999) grew European beech seedlings in glasshouses maintained at average atmospheric CO<sub>2</sub> concentrations of either 367 or 667 ppm for a period of one year. Then, throughout the following year, in addition to being exposed to the same set of CO<sub>2</sub> concentrations the seedlings were exposed to either ambient or twice-ambient levels of O<sub>3</sub>. This protocol revealed that elevated O<sub>3</sub> significantly reduced photosynthesis in beech seedlings grown at ambient CO<sub>2</sub> concentrations by a factor of approximately three. In contrast, in the CO<sub>2</sub>-enriched air the seedlings did not exhibit *any* photosynthetic reduction due to the doubled

O<sub>3</sub> concentrations. In fact, the photosynthetic rates of the CO<sub>2</sub>-enriched seedlings actually *rose by 8%* when simultaneously fumigated with elevated O<sub>3</sub>, leading the researchers to conclude that "long-term acclimation to elevated CO<sub>2</sub> supply does counteract the O<sub>3</sub>-induced decline of photosynthetic light and dark reactions."

Last of all, in a still longer study, Liu *et al.* (2004) grew 3- and 4-year-old beech seedlings for *two* growing seasons under the same experimental conditions as Liu *et al.* (2005) after the seedlings had been pre-acclimated for one year to either the ambient or elevated CO<sub>2</sub> treatment. At the end of the study, the plants were harvested and fresh weights and dry biomass values were determined for leaves, shoot axes, coarse roots and fine roots, as were carbohydrate (starch and soluble sugar) contents and concentrations for the same plant parts. This work falsified the hypothesis that "prolonged exposure to elevated CO<sub>2</sub> does not compensate for the adverse ozone effects on European beech," as it revealed that ALL "adverse effects of ozone on carbohydrate concentrations and contents were counteracted when trees were grown in elevated CO<sub>2</sub>."

These results are certainly good news for the biosphere (and especially for beech trees), as well as for human activities that result in CO<sub>2</sub> being emitted to the atmosphere. In addition to the latter activities having their own "excuse for being," they have the doubly good fortune of producing a byproduct that goes on to fight -- and *overpower* -- the deleterious consequences of one of the world's most devastating air pollutants.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/o/ozonebeech.php>.

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#### 6.3.5.2.3. BIRCH

At the FACE facility near Rhinelander, Wisconsin, USA, King *et al.* (2001) grew a mix of paper birch and quaking aspen trees in 30-m diameter plots that were maintained at atmospheric  $\text{CO}_2$  concentrations of 360 and 560 ppm with and without exposure to elevated  $\text{O}_3$  (1.5 times the ambient  $\text{O}_3$  concentration) for a period of two years. In their study of the belowground environment of the trees, they found that the extra  $\text{O}_3$  had no effect on the growth of fine roots over that time period, but that elevated  $\text{O}_3$  and  $\text{CO}_2$  together increased the fine-root biomass of the mixed stand by 83%.

One year later at the same FACE facility, Oksanen *et al.* (2001) observed  $\text{O}_3$ -induced injuries in the thylakoid membranes of the chloroplasts of the birch trees' leaves; but the injuries were partially ameliorated in the elevated  $\text{CO}_2$  treatment. And in a study conducted two years later, Oksanen *et al.* (2003) say they "were able to visualize and locate ozone-induced  $\text{H}_2\text{O}_2$  accumulation within leaf mesophyll cells, and relate oxidative stress with structural injuries." However, they report that " $\text{H}_2\text{O}_2$  accumulation was found only in ozone-exposed leaves and not in the presence of elevated  $\text{CO}_2$ ," adding that " $\text{CO}_2$  enrichment appears to alleviate chloroplastic oxidative stress."

Across the Atlantic in Finland, Kull *et al.* (2003) constructed open-top chambers around two clones (V5952 and K1659) of silver birch saplings that were rooted in the ground and had been growing there for the past seven years. These chambers were fumigated with air containing 360 and 720 ppm CO<sub>2</sub> in combination with 30 and 50 ppb O<sub>3</sub> for two growing seasons, after which it was noted that the extra O<sub>3</sub> had significantly decreased branching in the trees' crowns. This malady, however, was almost completely ameliorated by a doubling of the air's CO<sub>2</sub> concentration. In addition, after one more year of study, Eichelmann *et al.* (2004) reported that, by itself, the increase in the air's CO<sub>2</sub> content increased the average net photosynthetic rates of both clones by approximately 16%, while the increased O<sub>3</sub> by itself caused a 10% decline in the average photosynthetic rate of clone V5952, but not of clone K1659. When both trace gases were *simultaneously* increased, however, the photosynthetic rate of clone V5952 once again experienced a 16% increase in net photosynthesis, as if the extra O<sub>3</sub> had had no effect when applied in the presence of the extra CO<sub>2</sub>.

After working with the same trees for one additional year, Riikonen *et al.* (2004) harvested them and reported finding that "the negative effects of elevated O<sub>3</sub> were found mainly in ambient CO<sub>2</sub>, not in elevated CO<sub>2</sub>." In fact, whereas doubling the air's O<sub>3</sub> concentration decreased total biomass production by 13% across both clones, simultaneously doubling the air's CO<sub>2</sub> concentration *increased* total biomass production by 30%, thereby *more* than compensating for the deleterious consequences of doubling the atmospheric ozone concentration.

In commenting on this ameliorating effect of elevated CO<sub>2</sub>, the team of Finnish scientists said it "may be associated with either increased detoxification capacity as a consequence of higher carbohydrate concentrations in leaves grown in elevated CO<sub>2</sub>, or decreased stomatal conductance and thus decreasing O<sub>3</sub> uptake in elevated CO<sub>2</sub> conditions (e.g., Rao *et al.*, 1995)." They also noted that "the ameliorating effect of elevated CO<sub>2</sub> is in accordance with the results of single-season open-top chamber and growth chamber studies on small saplings of various deciduous tree species (Mortensen 1995; Dickson *et al.*, 1998; Loats and Rebeck, 1999) and long-term open-field and OTC studies with aspen and yellow-poplar (Percy *et al.*, 2002; Rebeck and Scherzer, 2002)."

In another paper to come out of the Finnish silver birch study, Peltonen *et al.* (2005) evaluated the impacts of doubled atmospheric CO<sub>2</sub> and O<sub>3</sub> concentrations on the accumulation of 27 phenolic compounds in the leaves of the trees, finding that elevated CO<sub>2</sub> increased the concentration of phenolic acids (+25%), myricetin glycosides (+18%), catechin derivatives (+13%) and soluble condensed tannins (+19%). Elevated O<sub>3</sub>, on the other hand, increased the concentration of one glucoside by 22%, chlorogenic acid by 19%, and flavone aglycons by 4%. *However*, Peltonen *et al.* say that this latter O<sub>3</sub>-induced production of antioxidant phenolic compounds "did not seem to protect the birch leaves from detrimental O<sub>3</sub> effects on leaf weight and area, but may have even exacerbated them." Last of all, in the combined elevated CO<sub>2</sub> and O<sub>3</sub> treatment, they found that "elevated CO<sub>2</sub> did seem to protect the leaves from elevated O<sub>3</sub> because all the O<sub>3</sub>-derived effects on the leaf phenolics and traits were prevented by elevated CO<sub>2</sub>."

Meanwhile, back at the FACE facility near Rhinelander, Wisconsin, USA, Agrell *et al.* (2005) examined the effects of ambient and elevated concentrations of atmospheric CO<sub>2</sub> and O<sub>3</sub> on the foliar chemistry of birch and aspen trees, plus the consequences of these effects for host plant preferences of forest tent caterpillar larvae. In doing so, they found that "the only chemical component showing a somewhat consistent co-variation with larval preferences was condensed tannins," and they discovered that "the tree becoming relatively less preferred as a result of CO<sub>2</sub> or O<sub>3</sub> treatment was in general also the one for which average levels of condensed tannins were most positively (or least negatively) affected by that treatment."

In this regard, it is of interest to note that the mean condensed tannin concentration of birch leaves was 18% higher in the elevated CO<sub>2</sub> and O<sub>3</sub> treatment. Consequently, as atmospheric concentrations of CO<sub>2</sub> and O<sub>3</sub> continue to rise, the increases in condensed tannin concentrations likely to occur in the foliage of birch trees should lead to their leaves becoming less preferred for consumption by the dreaded forest tent caterpillar, which according to Agrell *et al.* is "an eruptive generalist defoliator in North American hardwood forests, causing extensive damage during outbreak years (Fitzgerald, 1995)." Also, because the amount of methane expelled in the breath of ruminants is an inverse function of the condensed tannin concentration of the foliage they consume (see Tannins in our Subject Index), the increased foliage tannin concentrations likely to exist in a high-CO<sub>2</sub> world of the future should result in less methane being released to the atmosphere via ruminants ingesting such foliage, which phenomenon would tend to decrease the impetus for methane-induced global warming.

Concurrent with the work of Agrell *et al.*, King *et al.* (2005) evaluated the effect of CO<sub>2</sub> enrichment alone, O<sub>3</sub> enrichment alone, and the net effect of both CO<sub>2</sub> and O<sub>3</sub> enrichment together on the growth of the Rhinelander birch trees, finding that relative to the ambient-air control treatment, elevated CO<sub>2</sub> increased total biomass by 45% in the aspen-birch community, while elevated O<sub>3</sub> caused a 13% reduction in total biomass relative to the control. Of most interest of all, the combination of elevated CO<sub>2</sub> and O<sub>3</sub> resulted in a total biomass increase of 8.4% relative to the control aspen-birch community. King *et al.* thus concluded that "exposure to even moderate levels of O<sub>3</sub> significantly reduces the capacity of net primary productivity to respond to elevated CO<sub>2</sub> in some forests." Consequently, they suggested it makes sense to move forward with technologies that reduce anthropogenic precursors to photochemical O<sub>3</sub> formation, because the implementation of such a policy would decrease an important constraint on the degree to which forest ecosystems can positively respond to the ongoing rise in the air's CO<sub>2</sub> concentration.

One final paper to come out of the Finnish silver birch study was that of Kostianen *et al.* (2006), who studied the effects of elevated CO<sub>2</sub> and O<sub>3</sub> on various wood properties. Their work revealed that the elevated CO<sub>2</sub> treatment had no effect on wood structure, but that it increased annual ring width by 21%, woody biomass by 23% and trunk starch concentration by 7%. Elevated O<sub>3</sub>, on the other hand, decreased stem vessel percentage in one of the clones by 10%; but it had no effect on vessel percentage in the presence of elevated CO<sub>2</sub>.



In discussing their results, Kostianen *et al.* note that "in the xylem of angiosperms, water movement occurs principally in vessels (Kozlowski and Pallardy, 1997)," and that "the observed decrease in vessel percentage by elevated O<sub>3</sub> may affect water transport," obviously lowering it. *However*, as they continue, "elevated CO<sub>2</sub> ameliorated the O<sub>3</sub>-induced decrease in vessel percentage." In addition, they note that "the concentration of nonstructural carbohydrates (starch and soluble sugars) in tree tissues is considered a measure of carbon shortage or surplus for growth (Korner, 2003)." Hence, they conclude that "starch accumulation observed under elevated CO<sub>2</sub> in this study indicates a surplus of carbohydrates produced by enhanced photosynthesis of the same trees (Riikonen *et al.*, 2004)." In addition, they report that "during winter, starch reserves in the stem are gradually transformed to soluble carbohydrates involved in freezing tolerance (Bertrand *et al.*, 1999; Piispanen and Saranpaa, 2001), so the increase in starch concentration may improve acclimation in winter." Considering these several responses, therefore, it can be appreciated that the ongoing rise in the air's CO<sub>2</sub> content should be a boon to silver birch (and likely many other trees) in both summer *and* winter in both pristine *and* ozone-polluted air.

Rounding out the suite of Rhinelander FACE studies of paper birch is the report of Darbah *et al.* (2007), who found that the total number of trees that flowered increased by 139% under elevated CO<sub>2</sub> but only 40% under elevated O<sub>3</sub>. Likewise, with respect to the quantity of flowers produced, they found that elevated CO<sub>2</sub> led to a 262% increase, while elevated O<sub>3</sub> led to only a 75% increase. They also determined that elevated CO<sub>2</sub> had significant positive effects on birch catkin size, weight, and germination success rate, with elevated CO<sub>2</sub> increasing the germination rate of birch by 110%, decreasing seedling mortality by 73%, increasing seed weight by 17% and increasing new seedling root length by 59%. On the other hand, they found that just the *opposite* was true of elevated O<sub>3</sub>, as it decreased the germination rate of birch by 62%, decreased seed weight by 25%, and increased new seedling root length by only 15%.

In discussing their findings, Darbah *et al.* additionally report that "the seeds produced under elevated O<sub>3</sub> had much less stored carbohydrate, lipids, and proteins for the newly developing seedlings to depend on and, hence, the slow growth rate." As a result, they conclude that "seedling recruitment will be enhanced under elevated CO<sub>2</sub> but reduced under elevated O<sub>3</sub>," which is another important reason to hope that the atmosphere's CO<sub>2</sub> concentration continues to climb as long as the air's O<sub>3</sub> content is in a significantly ascending mode.

In summary, from their crowns to their roots, birch trees are generally negatively affected by rising ozone concentrations. When the air's CO<sub>2</sub> content is also rising, however, these negative consequences may often be *totally eliminated* and replaced by *positive* responses.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/o/ozonebirch.php>.

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#### 6.3.5.2.4. YELLOW-POPLAR

Scherzel *et al.* (1998) grew yellow-poplar seedlings in open-top chambers for four years at three different combinations of atmospheric O<sub>3</sub> and CO<sub>2</sub> -- (1) ambient O<sub>3</sub> and ambient CO<sub>2</sub>, (2) doubled O<sub>3</sub> and ambient CO<sub>2</sub>, and (3) doubled O<sub>3</sub> and doubled CO<sub>2</sub> -- to study the interactive effects of these gases on leaf-litter decomposition. This experiment revealed that the

decomposition rates of yellow-poplar leaves were similar for all three treatments for nearly five months, after which time litter produced in the elevated O<sub>3</sub> and elevated CO<sub>2</sub> air decomposed at a significantly slower rate, such that even after two years of decomposition, litter from the elevated O<sub>3</sub> and elevated CO<sub>2</sub> treatment still contained about 12% more biomass than litter produced in the other two treatments. This reduced rate of decomposition under elevated O<sub>3</sub> and CO<sub>2</sub> conditions will likely result in greater carbon sequestration in soils supporting yellow-poplar trees over the next century or more.

Loats and Rebbeck (1999) grew yellow-poplar seedlings for ten weeks in pots they placed within growth chambers filled with ambient air, air with twice the ambient CO<sub>2</sub> concentration, air with twice the ambient O<sub>3</sub> concentration, and air with twice the ambient CO<sub>2</sub> and O<sub>3</sub> concentrations to determine the effects of elevated CO<sub>2</sub> and O<sub>3</sub> on photosynthesis and growth in this deciduous tree species. In doing so, they found that doubling the air's CO<sub>2</sub> concentration increased the rate of net photosynthesis by 55% in ambient O<sub>3</sub> air, and that at twice the ambient level of O<sub>3</sub> it stimulated net photosynthesis by an average of 50%. Similarly, the doubled CO<sub>2</sub> concentration significantly increased total biomass by 29%, while the doubled O<sub>3</sub> concentration had little impact on growth.

Last of all, Rebbeck *et al.* (2004) grew yellow poplar seedlings for five years within open-top chambers in a field plantation at Delaware, Ohio, USA, exposing them continuously from mid-May through mid-October of each year to either (1) charcoal-filtered air to remove ambient O<sub>3</sub>, (2) ambient O<sub>3</sub>, (3) 1.5 times ambient O<sub>3</sub>, and (4) 1.5 times ambient O<sub>3</sub> plus 350 ppm CO<sub>2</sub> above ambient CO<sub>2</sub>, while they periodically measured a number of plant parameters and processes. Throughout the study, the trees were never fertilized, and they received no supplemental water beyond some given in the first season.

Averaged over the experiment's five growing seasons, the midseason net photosynthetic rate of upper canopy foliage at saturating light intensities declined by 10% when the trees were grown in ambient O<sub>3</sub>-air and by 14% when they were grown in elevated O<sub>3</sub>-air, when compared to the trees that were grown in the charcoal-filtered air, while seasonal net photosynthesis of foliage grown in the combination of elevated O<sub>3</sub> and elevated CO<sub>2</sub> was 57-80% higher than it was in the trees exposed to elevated O<sub>3</sub> alone. There was also no evidence of any photosynthetic down regulation in the trees exposed to the elevated O<sub>3</sub> and CO<sub>2</sub> air, with some of the highest rates being observed during the final growing season. Consequently, Rebbeck *et al.* concluded that "elevated CO<sub>2</sub> may ameliorate the negative effects of increased tropospheric O<sub>3</sub> on yellow-poplar." In fact, their results suggest that a nominally doubled atmospheric CO<sub>2</sub> concentration *more* than compensates for the deleterious effects of a 50% increase in ambient O<sub>3</sub> levels ... and by several times over.

As the air's CO<sub>2</sub> content continues to rise, therefore, earth's yellow-poplar trees will likely display substantial increases in photosynthetic rate and biomass production, even under conditions of elevated O<sub>3</sub> concentrations; and the soils in which the trees grow should sequester ever greater quantities of carbon.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/o/ozoneyellowpoplar.php>.

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### 6.3.6. Low Temperature Tolerance

Only a handful of studies have attempted to determine what relationship, if any, exists between atmospheric CO<sub>2</sub> enrichment and the ability of plants to withstand the rigors of cold temperatures. Nevertheless, some tantalizing things have been learned.

Loik *et al.* (2000) grew three *Yucca* species (*brevifolia*, *schidigera*, and *whipplei*) in pots placed within glasshouses maintained at atmospheric CO<sub>2</sub> concentrations of 360 and 700 ppm and day/night air temperatures of 40/24°C for seven months, after which some of the plants were subjected to a two-week day/night air temperature treatment of 20/5°C. In addition, leaves from each *Yucca* species were removed and placed in a freezer that was cooled at a rate of 3°C per hour until a minimum temperature of -15°C was reached. These manipulations indicated that elevated CO<sub>2</sub> lowered the air temperature at which 50% low-temperature-induced cell mortality occurred by 1.6, 1.4 and 0.8°C in *brevifolia*, *schidigera* and *whipplei*, respectively. And on the basis of the result obtained for *Y. brevifolia*, Dole *et al.* (2003) estimated that "the increase in freezing tolerance caused by doubled CO<sub>2</sub> would increase the potential habitat of this species by 14%."

In contrast to these positive results, Obrist *et al.* (2001) observed just the opposite response. In an open-top chamber study of a temperate grass ecosystem growing on a nutrient-poor calcareous soil in northwest Switzerland, portions of which had been exposed to atmospheric CO<sub>2</sub> concentrations of 360 and 600 ppm for a period of six years, they determined that the average temperature at which 50% low-temperature-induced leaf mortality occurred in five prominent species actually *rose* by an average of 0.7°C in response to the extra 240 ppm of CO<sub>2</sub> employed in their experiment.

Most relevant investigations, however, have produced evidence of *positive* CO<sub>2</sub> effects on plant low temperature tolerance. Sigurdsson (2001), for example, grew black cottonwood seedlings near Gunnarsholt, Iceland within closed-top chambers maintained at ambient and twice-

ambient atmospheric CO<sub>2</sub> concentrations for a period of three years, finding that elevated CO<sub>2</sub> tended to hasten the end of the growing season. This effect was interpreted as enabling the seedlings to better avoid the severe cold-induced dieback of newly-produced tissues that often occurs with the approach of winter in this region. Likewise, Wayne *et al.* (1998) found that yellow birch seedlings grown at an atmospheric CO<sub>2</sub> concentration of 800 ppm exhibited greater dormant bud survivorship at low air temperatures than did seedlings grown at 400 ppm CO<sub>2</sub>.

Schwanz and Polle (2001) investigated the effects of elevated CO<sub>2</sub> on chilling stress in micropropagated hybrid poplar clones that were subsequently potted and transferred to growth chambers maintained at either ambient (360 ppm) or elevated (700 ppm) CO<sub>2</sub> for a period of three months. They determined that "photosynthesis was less diminished and electrolyte leakage was lower in stressed leaves from poplar trees grown under elevated CO<sub>2</sub> as compared with those from ambient CO<sub>2</sub>." Although severe chilling did cause pigment and protein degradation in all stressed leaves, the damage was expressed to a lower extent in leaves from the elevated CO<sub>2</sub> treatment. This CO<sub>2</sub>-induced chilling protection was determined to be accompanied by a rapid induction of superoxide dismutase activity, as well as by slightly higher stabilities of other antioxidative enzymes.

Another means by which chilling-induced injury may be reduced in CO<sub>2</sub>-enriched air is suggested by the study of Sgherri *et al.* (1998), who reported that raising the air's CO<sub>2</sub> concentration from 340 to 600 ppm increased lipid concentrations in alfalfa thylakoid membranes while simultaneously inducing a higher degree of unsaturation in the most prominent of those lipids. Under well-watered conditions, for example, the 76% increase in atmospheric CO<sub>2</sub> enhanced overall thylakoid lipid concentration by about 25%, while it increased the degree of unsaturation of the two main lipids by approximately 17% and 24%. Under conditions of water stress, these responses were found to be even greater, as thylakoid lipid concentration rose by approximately 92%, while the degree of unsaturation of the two main lipids rose by about 22% and 53%.

What do these observations have to do with a plant's susceptibility to chilling injury? According to a number of studies conducted over the past decade, *a lot*.

Working with wild-type *Arabidopsis thaliana* and two mutants deficient in thylakoid lipid unsaturation, Hugly and Somerville (1992) found that "chloroplast membrane lipid polyunsaturation contributes to the low-temperature fitness of the organism," and that it "is required for some aspect of chloroplast biogenesis." When lipid polyunsaturation was low, for example, they observed "dramatic reductions in chloroplast size, membrane content, and organization in developing leaves." Furthermore, there was a positive correlation "between the severity of chlorosis in the two mutants at low temperatures and the degree of reduction in polyunsaturated chloroplast lipid composition."

Working with tobacco, Kodama *et al.* (1994) demonstrated that the low-temperature-induced suppression of leaf growth and concomitant induction of chlorosis observed in wild-type plants

was much less evident in transgenic plants containing a gene that allowed for greater expression of unsaturation in the fatty acids of leaf lipids. This observation and others led them to conclude that substantially unsaturated fatty acids "are undoubtedly an important factor contributing to cold tolerance."

In a closely related study, Moon *et al.* (1995) found that heightened unsaturation of the membrane lipids of chloroplasts stabilized the photosynthetic machinery of transgenic tobacco plants against low-temperature photoinhibition "by accelerating the recovery of the photosystem II protein complex." Likewise, Kodama *et al.* (1995), also working with transgenic tobacco plants, showed that increased fatty acid desaturation is one of the prerequisites for normal leaf development at low, nonfreezing temperatures; and Ishizaki-Nishizawa *et al.* (1996) demonstrated that transgenic tobacco plants with a reduced level of saturated fatty acids in most membrane lipids "exhibited a significant increase in chilling resistance."

These observations are laden with significance for earth's agro-ecosystems. Many economically important crops, such as rice, maize and soybeans, are classified as *chilling-sensitive*; and they experience injury or death at temperatures between 0 and 15°C (Lyons, 1973). If atmospheric CO<sub>2</sub> enrichment enhances their production and degree-of-unsaturation of thylakoid lipids, as it does in alfalfa, a continuation of the ongoing rise in the air's CO<sub>2</sub> content could increase the abilities of these critically important agricultural species to withstand periodic exposure to debilitating low temperatures; and this phenomenon could provide the extra boost in food production that will be needed to sustain our increasing numbers in the years and decades ahead.

Earth's natural ecosystems would also benefit from a CO<sub>2</sub>-induced increase in thylakoid lipids containing more-highly-unsaturated fatty acids. Many plants of tropical origin, for example, suffer cold damage when temperatures fall below 20°C (Graham and Patterson, 1982); and with improved lipid characteristics provided by the ongoing rise in the air's CO<sub>2</sub> content, such plants would be able to expand their ranges both poleward and upward in a higher-CO<sub>2</sub> world.

Clearly, more research remains to be done before we can accurately assess the extent of these potential biological benefits. In particular, we must conduct more studies of the effects of atmospheric CO<sub>2</sub> enrichment on the properties of thylakoid lipids in a greater variety of plants; and, *in the same experiments*, we must assess the efficacy of these lipid property changes in enhancing plant tolerance of low temperatures. Such studies should rank high on the to-do list of relevant funding agencies.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/f/frosthardeness.php>.

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### 6.3.7. Nitrogen

Numerous studies have investigated the effects of different soil nitrogen (N) concentrations on plant responses to increases in the air's CO<sub>2</sub> content, as it has been claimed that a deficiency of soil nitrogen lessens the relative growth stimulation in plants that is typically provided by elevated concentrations of atmospheric CO<sub>2</sub>. In this section, we evaluate the credibility of that claim for various crops, fungi, grasses and trees.

The results of these experiments indicate that some plants sometimes will not respond at all to atmospheric CO<sub>2</sub> enrichment at low levels of soil N, while some will. In fact, some plants respond equally well to increases in the air's CO<sub>2</sub> content when growing in soils exhibiting a whole range of N concentrations. Most common of all, however, is the observation that plants respond ever better to rising atmospheric CO<sub>2</sub> concentrations as soil N concentrations rise. Interestingly, the current state of earth's atmosphere and land surface is one of jointly increasing CO<sub>2</sub> and N concentrations, respectively. Hence, the outlook is good for continually increasing terrestrial vegetative productivity in the years and decades ahead, as these trends continue.

Additional information on this topic, including reviews on nitrogen not discussed here, can be found at [http://www.co2science.org/subject/g/subject\\_g.php](http://www.co2science.org/subject/g/subject_g.php) under the heading Growth Response to CO<sub>2</sub> With Other Variables: Nutrients: Nitrogen, as well as at [http://www.co2science.org/subject/n/subject\\_n.php](http://www.co2science.org/subject/n/subject_n.php) under the headings Nitrogen, Nitrogen Fixation and Nitrogen Use Efficiency.

#### 6.3.7.1. Crops

##### 6.3.7.1.1. RICE

Does a deficiency of soil nitrogen lessen the relative growth and yield stimulation of rice that is typically provided by elevated levels of atmospheric CO<sub>2</sub>?

In exploring this question, Weerakoon *et al.* (1999) grew seedlings of two rice cultivars for 28 days in glasshouses maintained at atmospheric CO<sub>2</sub> concentrations of 373, 545, 723 and 895 ppm under conditions of low, medium and high soil nitrogen content. After four weeks of treatment, photosynthesis was found to significantly increase with increasing nitrogen availability and atmospheric CO<sub>2</sub> concentration. Averaged across all nitrogen regimes, plants grown at 895 ppm CO<sub>2</sub> exhibited photosynthetic rates that were 50% greater than those observed in plants grown at ambient CO<sub>2</sub>. Total plant dry weight also increased with increasing atmospheric CO<sub>2</sub>. In addition, the percentage growth enhancement resulting from CO<sub>2</sub> enrichment increased with increasing soil nitrogen; from 21% at the lowest soil nitrogen concentration to 60% at the highest concentration.

Using a different CO<sub>2</sub> enrichment technique, Weerakoon *et al.* (2000) grew rice in open-top chambers maintained at atmospheric CO<sub>2</sub> concentrations of approximately 350 and 650 ppm during a wet and dry growing season and under a range of soil nitrogen contents. Early in both growing seasons, plants exposed to elevated atmospheric CO<sub>2</sub> concentrations intercepted significantly more sunlight than plants fumigated with ambient air, due to CO<sub>2</sub>-induced increases in leaf area index. This phenomenon occurred regardless of soil nitrogen content, but disappeared shortly after canopy closure in all treatments. Later, mature canopies achieved similar leaf area indexes at identical levels of soil nitrogen supply; but mean season-long radiation use efficiency, which is the amount of biomass produced per unit of solar radiation intercepted, was 35% greater in CO<sub>2</sub>-enriched vs. ambiently-grown plants and tended to increase with increasing soil nitrogen content.

Utilizing yet a third approach to enriching the air about a crop with elevated levels of atmospheric CO<sub>2</sub>, Kim *et al.* (2003) grew rice crops from the seedling stage to maturity at atmospheric CO<sub>2</sub> concentrations of ambient and ambient plus 200 ppm using FACE technology and three levels of applied nitrogen -- low (LN, 4 g N m<sup>-2</sup>), medium (MN, 8 and 9 g N m<sup>-2</sup>) and high (HN, 15 g N m<sup>-2</sup>) -- for three cropping seasons (1998-2000). They report that "the yield response to elevated CO<sub>2</sub> in crops supplied with MN (+14.6%) or HN (+15.2%) was about twice that of crops supplied with LN (+7.4%)," confirming the importance of nitrogen availability to the response of rice to atmospheric CO<sub>2</sub> enrichment previously determined by Kim *et al.* (2001) and Kobaysahi *et al.* (2001).

In light of these observations, it would appear that the maximum benefits of elevated levels of atmospheric CO<sub>2</sub> for the growth and grain production of rice cannot be realized in soils that are highly deficient in nitrogen, but that increasing nitrogen concentrations above what is considered adequate may not result in proportional gains in CO<sub>2</sub>-induced growth and yield enhancement.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/n/nitrogenrice.php>.

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#### 6.3.7.1.2. WHEAT

Smart *et al.* (1998) grew wheat from seed for 23 days in controlled environment chambers maintained at atmospheric CO<sub>2</sub> concentrations of 360 and 1000 ppm and two concentrations of soil nitrate, finding that the extra CO<sub>2</sub> increased average plant biomass by approximately 15%, irrespective of soil nitrogen content. In a more realistic FACE experiment, however, Brooks *et al.* (2000) grew spring wheat for two seasons at atmospheric CO<sub>2</sub> concentrations of 370 and 570 ppm at both high and low levels of nitrogen fertility; and they obtained *twice* the yield enhancement (16% vs. 8%) in the high nitrogen treatment.

In an experiment with one additional variable, Vilhena-Cardoso and Barnes (2001) grew spring wheat for two months in environmental chambers fumigated with air containing atmospheric CO<sub>2</sub> concentrations of either 350 or 700 ppm at ambient and elevated (75 ppb) ozone concentrations, while the plants were simultaneously subjected to either low, medium or high levels of soil nitrogen. With respect to biomass production, the elevated CO<sub>2</sub> treatment increased total plant dry weight by 44, 29 and 12% at the high, medium and low soil nitrogen levels, respectively. In addition, although elevated ozone alone reduced plant biomass, the simultaneous application of elevated CO<sub>2</sub> completely ameliorated its detrimental effects on biomass production, irrespective of soil nitrogen supply.

So why do the plants of some studies experience a major reduction in the relative growth stimulation provided by atmospheric CO<sub>2</sub> enrichment under low soil nitrogen conditions, while other studies find the aerial fertilization effect of elevated CO<sub>2</sub> to be independent of root-zone nitrogen concentration? Based on studies of both potted and hydroponically-grown plants, Farage *et al.* (1998) determined that low root-zone nitrogen concentrations need not lead to photosynthetic acclimation (less than maximum potential rates of photosynthesis) in elevated CO<sub>2</sub>, as long as root-zone nitrogen *supply* is adequate to meet plant nitrogen *needs* to maintain the enhanced relative growth rate that is made possible by atmospheric CO<sub>2</sub> enrichment. When supply cannot meet this need, as is often the case in soils with limited nitrogen reserves, the aerial fertilization effect of atmospheric CO<sub>2</sub> enrichment begins to be reduced and less-than-potential CO<sub>2</sub>-induced growth stimulation is observed. Nevertheless, the acclimation process is the plant's "first line of defense" to keep its productivity from falling even further than it otherwise would, as it typically mobilizes nitrogen from "excess" rubisco and sends it to more needy plant sink tissues to allow for their continued growth and development (Theobald *et al.*, 1998).

In conclusion, although atmospheric CO<sub>2</sub> enrichment tends to increase the growth and yield of wheat under a wide range of soil nitrogen concentrations, including some that are very low, considerably greater CO<sub>2</sub>-induced enhancements are possible when more soil nitrogen is

available, although the response can saturate at high soil nitrogen levels, with excess nitrogen providing little to no extra yield.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/n/nitrogenwheat.php>.

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### 6.3.7.1.3. OTHER

Zerihun *et al.* (2000) grew sunflowers for one month in pots of three different soil nitrogen concentrations that were placed within open-top chambers maintained at atmospheric CO<sub>2</sub> concentrations of 360 and 700 ppm. The extra CO<sub>2</sub> of the CO<sub>2</sub>-enriched chambers reduced average rates of root nitrogen uptake by about 25%, which reduction, by itself, would normally tend to reduce tissue nitrogen contents and the relative growth rates of the seedlings. However, the elevated CO<sub>2</sub> also increased photosynthetic nitrogen-use efficiency by an average of 50%, which increase normally tends to increase the relative growth rates of seedlings. Of these two competing effects, the latter was by far the more powerful, ultimately leading to an increase in whole plant biomass. After the one month of the study, for example, the CO<sub>2</sub>-enriched plants exhibited whole plant biomass values that were 44, 13 and 115% greater than those of the plants growing in ambient air at low, medium and high levels of soil nitrogen, respectively, thus demonstrating that low tissue nitrogen contents do not necessarily preclude a growth response to atmospheric CO<sub>2</sub> enrichment, particularly if photosynthetic nitrogen-use efficiency is enhanced, which is typically the case, as it was in this study. Nevertheless, the greatest CO<sub>2</sub>-induced growth increase of Zerihun *et al.*'s study was exhibited by the plants growing in the high soil nitrogen treatment.

Deng and Woodward (1998) grew strawberries in environment-controlled glasshouses maintained at atmospheric CO<sub>2</sub> concentrations of 390 and 560 ppm for nearly three months. In addition, the strawberries were supplied with fertilizers containing three levels of nitrogen. The extra CO<sub>2</sub> increased rates of net photosynthesis and total plant dry weight at all three nitrogen levels, but the increases were not significant. Nevertheless, they provided the CO<sub>2</sub>-enriched plants with enough additional sugar and physical mass to support significantly greater numbers of flowers and fruits than the plants grown at 390 ppm CO<sub>2</sub>. This effect consequently led to total fresh fruit weights that were 42 and 17% greater in the CO<sub>2</sub>-enriched plants that received the highest and lowest levels of nitrogen fertilization, respectively, once again indicating a greater growth response at higher nitrogen levels.

Newman *et al.* (2003) investigated the effects of two levels of nitrogen fertilization and an approximate doubling of the air's CO<sub>2</sub> concentration on the growth of tall fescue, which is an important forage crop. The plants with which they worked were initially grown from seed in greenhouse flats, but after sixteen weeks they were transplanted into 19-liter pots filled with potting media that received periodic applications of a slow-release fertilizer. Then, over the next two years of outdoor growth, they were periodically clipped, divided and repotted to ensure they did not become root-bound; and at the end of that time, they were placed within twenty 1.3-m-diameter open-top chambers, half of which were maintained at the ambient atmospheric CO<sub>2</sub> concentration and half of which were maintained at an approximately doubled CO<sub>2</sub> concentration of 700 ppm. In addition, half of the pots in each CO<sub>2</sub> treatment received 0.0673 kg N m<sup>-2</sup> applied over a period of three consecutive days, while half of them received only one-tenth that amount, with the entire procedure being repeated three times during the course of the 12-week experiment. As to what was learned, Newman *et al.* report that the plants grown in the high-CO<sub>2</sub> air photosynthesized 15% more and produced 53% more dry matter (DM) under low N conditions and 61% more DM under high N conditions. In addition, they report that the % organic matter (OM) was little changed, except under elevated CO<sub>2</sub> and high N, when %OM (as %DM) increased by 3%. In this study too, therefore, the greatest relative increase in productivity occurred under high, as opposed to low, soil N availability.

Demmers-Derks *et al.* (1998) grew sugar beets as an annual crop in controlled-environment chambers at atmospheric CO<sub>2</sub> concentrations of 360 and 700 ppm and air temperatures of ambient and ambient plus 3°C for three consecutive years. In addition to being exposed to these CO<sub>2</sub> and temperature combinations, the sugar beets were supplied with solutions of low and high nitrogen content. Averaged across all three years and both temperature regimes, the extra CO<sub>2</sub> of this study enhanced total plant biomass by 13 and 25% in the low and high nitrogen treatments, respectively. In addition, it increased root biomass by 12 and 26% for the same situations. Thus, as was the case with sunflowers, strawberries and tall fescue, elevated CO<sub>2</sub> elicited the largest growth responses in the sugar beets that received a high, as opposed to a low, supply of nitrogen.

Also working with sugar beets were Romanova *et al.* (2002), who grew them from seed for one month in controlled environment chambers maintained at atmospheric CO<sub>2</sub> concentrations of 350 and 700 ppm, while fertilizing them with three different levels of nitrate-nitrogen. In this study, the plants grown in CO<sub>2</sub>-enriched air exhibited rates of net photosynthesis that were approximately 50% greater than those displayed by the plants grown in ambient air, regardless of soil nitrate availability. These CO<sub>2</sub>-induced increases in photosynthetic carbon uptake contributed to 60, 40 and 30% aboveground organ dry weight increases in plants receiving one-half, standard, and three-fold levels of soil nitrate, respectively. Root weights, however, were less responsive to atmospheric CO<sub>2</sub> enrichment, displaying 10 and 30% increases in dry weight at one-half and standard nitrate levels, but no increase at the high soil nitrate concentration. In this study, therefore, the role of soil nitrogen fertility was clearly *opposite* to that observed in the four prior studies in the case of *aboveground* biomass production, but was mixed in the case of belowground biomass production.

Switching to barley, Fangmeier *et al.* (2000) grew plants in containers placed within open-top chambers maintained at atmospheric CO<sub>2</sub> concentrations of either 360 or 650 ppm and either a high or low nitrogen fertilization regime; and in this case, as in the case of the aboveground biomass response of the sugar beets of Romanova *et al.*, the elevated CO<sub>2</sub> had the greatest relative impact on yield when the plants were grown under the *less-than-optimum low*-nitrogen regime, i.e., a 48% increase vs. 31% under high-nitrogen conditions.

Last of all, we report the pertinent results of the review and analysis of Kimball *et al.* (2002), who summarized the findings of most Free-Air CO<sub>2</sub> Enrichment (FACE) studies conducted on agricultural crops since the introduction of that technology back in the late 1980s. In response to a 300-ppm increase in the air's CO<sub>2</sub> concentration, rates of net photosynthesis in several C<sub>3</sub> grasses were enhanced by an average of 46% under conditions of ample soil nitrogen supply and by 44% when nitrogen was limiting to growth. With respect to aboveground biomass production, the differential was much larger, with the C<sub>3</sub> grasses wheat, rice and ryegrass experiencing an average increase of 18% at ample nitrogen but only 4% at low nitrogen; while with respect to belowground biomass production, they experienced an average increase of 70% at ample nitrogen and 58% at low nitrogen. Similarly, clover experienced a 38% increase in belowground biomass production at ample soil nitrogen, and a 32% increase at low soil nitrogen. Finally, with respect to agricultural yield, which is the bottom line in terms of food and fiber production, wheat and ryegrass experienced an average increase of 18% at ample nitrogen, while wheat experienced only a 10% increase at low nitrogen.

In light of these several results, it can be safely concluded that although there are some significant exceptions to the rule, *most* agricultural crops *generally* experience *somewhat* greater CO<sub>2</sub>-induced relative (percentage) increases in net photosynthesis and biomass production when soil nitrogen concentrations are higher rather than lower.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/n/nitrogenagriculture.php>.

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### 6.3.7.2. Fungi

Nearly all of earth's plants become involved in intimate relationships with different fungal species at one point or another in their life cycles. Among other things, the fungi commonly aid plants in the acquisition of water and important soil nutrients. In addition, fungal-plant interactions are often impacted by variations in both atmospheric CO<sub>2</sub> and soil nitrogen concentrations. In this subsection, we review how various aspects of fungal-plant interactions are influenced by elevated CO<sub>2</sub> under varying soil nitrogen regimes.

In a one-year study conducted by Walker *et al.* (1998), ponderosa pine seedlings exposed to atmospheric CO<sub>2</sub> concentrations of 525 and 700 ppm displayed total numbers of ectomycorrhizal fungi on their roots that were 170 and 85% greater, respectively, than those observed on roots of ambiently-grown seedlings.

In the study of Rillig *et al.* (1998), three grasses and two herbs fumigated with ambient air and air containing an extra 350 ppm CO<sub>2</sub> for four months displayed various root infection responses by arbuscular mycorrhizal fungi, which varied with soil nitrogen supply. At low soil nitrogen

contents, elevated CO<sub>2</sub> increased the percent root infection by this type of fungi in all five annual grassland species. However, at high soil nitrogen contents, this trend was reversed in four of the five species.

Finally, in the study of Rillig and Allen (1998), several important observations were made with respect to the effects of elevated CO<sub>2</sub> and soil nitrogen status on fungal-plant interactions. First of all, after growing three-year-old shrubs at an atmospheric CO<sub>2</sub> concentration of 750 ppm for four months, they reported insignificant 19 and 9% increases in percent root infected by arbuscular mycorrhizal fungi at low and high soil nitrogen concentrations, respectively. However, elevated CO<sub>2</sub> significantly increased the percent root infection by arbuscules, which are the main structures involved in the symbiotic exchange of carbon and nutrients between a host plant and its associated fungi, by more than 14-fold at low soil nitrogen concentrations. In addition, the length of fungal hyphae more than doubled with atmospheric CO<sub>2</sub> enrichment in the low soil nitrogen regime. In the high soil nitrogen treatment, elevated CO<sub>2</sub> increased the percent root infection by vesicles, which are organs used by arbuscular mycorrhizal fungi for carbon storage, by approximately 2.5-fold.

In conclusion, these observations suggest that elevated CO<sub>2</sub> will indeed affect fungal-plant interactions in positive ways that often depend upon soil nitrogen status. Typically, it appears that CO<sub>2</sub>-induced stimulations of percent root infection by various fungal components is greater under lower, rather than higher, soil nitrogen concentrations. This tendency implies that elevated CO<sub>2</sub> will enhance fungal-plant interactions to a greater extent when soil nutrition is less-than-optimal for plant growth, which is the common case for most of earth's ecosystems that are not subjected to cultural fertilization practices typical of intensive agricultural production.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/n/nitrogenfungi.php>.

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### 6.3.7.3. Grasses

Perennial ryegrass (*Lolium perenne* L.) has been used as a model species in many experiments to help elucidate grassland responses to atmospheric CO<sub>2</sub> enrichment and soil nitrogen availability. In the FACE study of Rogers *et al.* (1998), for example, plants exposed to 600 ppm CO<sub>2</sub> exhibited a 35% increase in their photosynthetic rates without regard to soil nitrogen availability. However, when ryegrass was grown in plastic ventilated tunnels at twice-ambient concentrations of atmospheric CO<sub>2</sub>, the CO<sub>2</sub>-induced photosynthetic response was about 3-fold greater in a higher, as opposed to a lower, soil nitrogen regime (Casella and Soussana, 1997). Similarly, in an open-top chamber study conducted by Davey *et al.* (1999), it was reported that an atmospheric CO<sub>2</sub> concentration of 700 ppm stimulated photosynthesis by 30% in this species when it was grown with moderate, but not low, soil nitrogen availability. Thus, CO<sub>2</sub>-induced photosynthetic stimulations in perennial ryegrass can be influenced by soil nitrogen content, with greater positive responses typically occurring under higher, as opposed to lower, soil nitrogen availability.

With respect to biomass production, van Ginkel and Gorissen (1998) reported that a doubling of the atmospheric CO<sub>2</sub> concentration increased shoot biomass of perennial ryegrass by 28%, regardless of soil nitrogen concentration. In the more revealing six-year FACE study of Daepf *et al.* (2000), plants grown at 600 ppm CO<sub>2</sub> and high soil nitrogen availability continually increased their dry matter production over that observed in ambient-treatment plots, from 8% more in the first year to 25% more at the close of year six. When grown at a low soil nitrogen availability, however, CO<sub>2</sub>-enriched plants exhibited an initial 5% increase in dry matter production, which dropped to a negative 11% in year two; but this negative trend was thereafter turned around, and it continually rose to ultimately reach a 9% stimulation at the end of the study. Thus, these data demonstrate that elevated CO<sub>2</sub> increases perennial ryegrass biomass, even under conditions of low soil nitrogen availability, especially under conditions of long-term atmospheric CO<sub>2</sub> enrichment.

If perennial ryegrass is indeed representative of most grassland species, one would anticipate the remainder of this summary to include similar positive effects of CO<sub>2</sub> on the photosynthesis and biomass of other grasses, even under low nitrogen conditions; and that is exactly what the data reveal. Lutze *et al.* (1998), for example, reported that microcosms of the C<sub>3</sub> grass *Danthonia richardsonii* grown for four years in glasshouses fumigated with air containing 720 ppm CO<sub>2</sub> displayed total photosynthetic carbon gains that were always 15-34% higher than those of ambiently-grown microcosms, depending on the soil nitrogen concentration. In a clearer depiction of photosynthetic responses to soil nitrogen, Davey *et al.* (1999) noted that photosynthetic rates of *Agrostis capillaries* subjected to twice-ambient levels of atmospheric CO<sub>2</sub> for two years were 12 and 38% greater than rates measured in control plants grown at 350 ppm CO<sub>2</sub> under high and low soil nitrogen regimes, respectively. In addition, they also reported CO<sub>2</sub>-induced photosynthetic stimulations of 25 and 74% for *Trifolium repens* subjected to high and low soil nitrogen regimes, respectively. Thus, we see that the greatest CO<sub>2</sub>-induced percentage increase in photosynthesis can sometimes occur under the *least* favorable soil nitrogen conditions.

With respect to biomass production, Navas *et al.* (1999) reported that 60 days' exposure to 712 ppm CO<sub>2</sub> increased biomass production of *Danthonia richardsonii*, *Phalaris aquatica*, *Lotus pedunculatus*, and *Trifolium repens* across a large soil nitrogen gradient. With slightly more detail, Cotrufo and Gorissen (1997) reported average CO<sub>2</sub>-induced increases in whole-plant dry weights of *Agrostis capillaries* and *Festuca ovina* that were 20% greater than those of their respective controls, regardless of soil nitrogen availability. In the study of Ghannoum and Conroy (1998), three *Panicum* grasses grown for two months at twice-ambient levels of atmospheric CO<sub>2</sub> and high soil nitrogen availability displayed similar increases in total plant dry mass that were about 28% greater than those of their respective ambiently-grown controls. At low nitrogen, however, elevated CO<sub>2</sub> had no significant effect on the dry mass of two of the species, while it actually decreased that of the third species.

In summary, it is clear that atmospheric CO<sub>2</sub> enrichment stimulates photosynthesis and biomass production in grasses and grassland species when soil nitrogen availability is high and/or moderate. Under lower soil nitrogen conditions, it is also clear that atmospheric CO<sub>2</sub> enrichment can have the same positive effect on these parameters, but that it can also have a reduced positive effect, no effect, or (in one case) a negative effect. In light of the one long-term study that lasted six years, however, it is likely that – given enough time – grasslands have the ability to overcome soil nitrogen limitations and produce positive CO<sub>2</sub>-induced growth responses. Thus, because the rising CO<sub>2</sub> content of the air is likely to continue for a long time to come, occasional nitrogen limitations on the aerial fertilization effect of atmospheric CO<sub>2</sub> enrichment of grasslands will likely become less and less restrictive as time progresses.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/n/nitrogengrass.php>.

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#### 6.3.7.4. Trees

##### 6.3.7.4.1. ASPEN

Does a deficiency of soil nitrogen lessen the relative growth stimulation of quaking aspen (*Populus tremuloides* Michx) that is typically provided by elevated concentrations of atmospheric CO<sub>2</sub>?

In exploring this question, Kubiske *et al.* (1998) grew cuttings of four quaking aspen genotypes for five months at CO<sub>2</sub> concentrations of 380 or 720 ppm and low or high soil nitrogen in open-top chambers in the field in Michigan, USA. They found that the elevated CO<sub>2</sub> treatment significantly increased net photosynthesis, regardless of soil nitrogen content, although there were no discernible increases in aboveground growth within the five-month study period. Belowground, however, elevated CO<sub>2</sub> significantly increased fine root production, but only in the high soil nitrogen treatment.

Working at the same site, Zak *et al.* (2000) and Curtis *et al.* (2000) grew six aspen genotypes from cuttings in open-top chambers for 2.5 growing seasons at atmospheric CO<sub>2</sub> concentrations of 350 and 700 ppm on soils containing either adequate or inadequate supplies of nitrogen. Curtis *et al.* report that at the end of this period the trees growing in the doubled-CO<sub>2</sub> treatment exhibited rates of net photosynthesis that were 128% and 31% greater than those of the trees growing in the ambient-air treatment on the high- and low-nitrogen soils, respectively, while Zak *et al.* determined the CO<sub>2</sub>-induced biomass increases of the trees in the high- and low-nitrogen soils to be 38% and 16%, respectively.

In yet another study from the Michigan site, Mikan *et al.* (2000) grew aspen cuttings for two years in open-top chambers receiving atmospheric CO<sub>2</sub> concentrations of 367 and 715 ppm in soils of low and high soil nitrogen concentrations. They report finding that elevated CO<sub>2</sub> increased the total biomass of the aspen cuttings by 50% and 26% in the high and low soil nitrogen treatments, respectively, and that it increased coarse root biomass by 78% and 24% in the same respective treatments.

Last of all, but again at the same site, Wang and Curtis (2001) grew cuttings of two male and two female aspen trees for about five months in open-top chambers maintained at atmospheric CO<sub>2</sub> concentrations of 380 and 765 ppm on soils of high and low nitrogen content. In the male cuttings, there was a modest difference in the CO<sub>2</sub>-induced increase in total biomass (58% and 66% in the high- and low-nitrogen soils, respectively), while in the female cuttings the difference was much greater (82% and 22% in the same respective treatments).

Considering the totality of these several observations, it would appear that the degree of soil nitrogen availability does indeed impact the aerial fertilization effect of atmospheric CO<sub>2</sub> enrichment on the growth of aspen trees by promoting a greater CO<sub>2</sub>-induced growth enhancement in soils of adequate, as opposed to insufficient, nitrogen content.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/n/nitrogenaspen.php>.

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#### 6.3.7.4.2. PINE

In a review of eleven of their previously published papers dealing with both loblolly pine (*Pinus taeda* L.) and ponderosa pine (*Pinus ponderosa* Dougl.), Johnson *et al.* (1998) report that when soil nitrogen levels were so low as to be extremely deficient, or so high as to be toxic, growth responses to atmospheric CO<sub>2</sub> enrichment in both species were negligible. For moderate soil nitrogen deficiencies, however, a doubling of the air's CO<sub>2</sub> content sometimes boosted growth by as much as 1,000%. In addition, atmospheric CO<sub>2</sub> enrichment mitigated the negative growth response of ponderosa pine to extremely high soil nitrogen concentrations.

In a second paper published by some of the same scientists in the same year, Walker *et al.* (1998) describe how they raised ponderosa pine tree seedlings for two growing seasons in open-top chambers having CO<sub>2</sub> concentrations of 350, 525 and 700 ppm on soils of low, medium and high nitrogen content. They report that elevated CO<sub>2</sub> had little effect on most growth parameters after the first growing season, the one exception being belowground biomass, which increased with both CO<sub>2</sub> and soil nitrogen. After two growing seasons, however, elevated CO<sub>2</sub> significantly increased all growth parameters, including tree height, stem diameter, shoot weight, stem volume and root volume, with the greatest responses typically occurring at the highest CO<sub>2</sub> concentration in the highest soil nitrogen treatment. Root volume at 700 ppm CO<sub>2</sub> and high soil nitrogen, for example, exceeded that of all other treatments by at least 45%, as did shoot volume by 42%. Similarly, at high CO<sub>2</sub> and soil nitrogen, coarse root and shoot weights exceeded those at ambient CO<sub>2</sub> and high nitrogen by 80 and 88%, respectively.

Walker *et al.* (2000) published another paper on the same trees and treatments after five years of growth. At this time, the trees exposed to the twice-ambient levels of atmospheric CO<sub>2</sub> had heights that were 43, 64 and 25% greater than those of the trees exposed to ambient air and conditions of high, medium and low levels of soil nitrogen, respectively. Similarly, the trunk diameters of the 700-ppm-trees were 24, 73 and 20% greater than the trunk diameters of the ambiently-grown trees exposed to high, medium and low levels of soil nitrogen.

Switching to a different species, Entry *et al.* (1998) grew one-year-old longleaf pine seedlings for 20 months in pots of high and low soil nitrogen content within open-top chambers maintained at atmospheric CO<sub>2</sub> concentrations of 365 or 720 ppm, finding that the elevated CO<sub>2</sub> caused no overall change in whole-plant biomass at low soil nitrogen, but that at high soil nitrogen, it increased it by 42%. After two years of these treatments, Runion *et al.* (1999) also reported that rates of net photosynthesis were about 50% greater in the high CO<sub>2</sub> treatment, irrespective of soil nitrogen content ... and water content too.

Last of all, Finzi and Schlesinger (2003) measured and analyzed the pool sizes and fluxes of inorganic and organic nitrogen (N) in the floor and top 30 cm of mineral soil of the Duke Forest at the five-year point of a long-term FACE study, where half of the experimental plots are enriched with an extra 200 ppm of CO<sub>2</sub>. In commencing this study, they had originally hypothesized that "the increase in carbon fluxes to the microbial community under elevated CO<sub>2</sub> would increase the rate of N immobilization over mineralization," leading to a decline in

the significant CO<sub>2</sub>-induced stimulation of forest net primary production that developed over the first two years of the experiment (DeLucia *et al.*, 1999; Hamilton *et al.*, 2002). Quite to the contrary, however, they discovered "there was no statistically significant change in the cycling rate of N derived from soil organic matter under elevated CO<sub>2</sub>." Neither was the rate of net N mineralization significantly altered by elevated CO<sub>2</sub>, nor was there any statistically significant difference in the concentration or net flux of organic and inorganic N in the forest floor and top 30-cm of mineral soil after 5 years of CO<sub>2</sub> fumigation. Hence, at this stage of the study, they could find no support for their original hypothesis, which suggests that the growth stimulation provided by elevated levels of atmospheric CO<sub>2</sub> would gradually dwindle away to something rather insignificant before the stand reached its equilibrium biomass, although they continue to cling to this unsubstantiated belief.

Considering the totality of these several observations, it would appear that the degree of soil nitrogen availability does indeed impact the aerial fertilization effect of atmospheric CO<sub>2</sub> enrichment on the growth of pine trees by promoting a greater CO<sub>2</sub>-induced growth enhancement in soils of adequate, as opposed to insufficient, nitrogen content. As in the case of aspen, however, there is evidence to suggest that at some point the response to increasing soil nitrogen saturates, and that higher N concentrations may sometimes even reduce the forest growth response to elevated CO<sub>2</sub>.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/n/nitrogenpine.php>.

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#### 6.3.7.4.3. SPRUCE

Egli *et al.* (1998) rooted saplings of different genotypes of Norway spruce (*Picea abies* L. Karst.) directly into calcareous or acidic soils in open-top chambers and exposed them to atmospheric CO<sub>2</sub> concentrations of 370 or 570 ppm and low or high soil nitrogen contents. They found that elevated CO<sub>2</sub> generally stimulated light-saturated rates of photosynthesis under all conditions by as much as 35%, regardless of genotype, which consistently led to increased aboveground biomass production, also regardless of genotype, as well as without respect to soil type or nitrogen content.

Murray *et al.* (2000) grew Sitka spruce (*Picea sitchensis* (Bong.) Carr.) seedlings for two years in pots within open-top chambers maintained at atmospheric CO<sub>2</sub> concentrations of 355 and 700 ppm. In the last year of the study, half of the seedlings received one-tenth of the optimal soil nitrogen supply recommended for this species, while the other half received twice the optimal amount. Under this protocol, the extra CO<sub>2</sub> increased the seedlings' light-saturated rates of net photosynthesis by 19% and 33% in the low- and high-nitrogen treatments, respectively, while it increased their total biomass by 0% and 37% in these same treatments. Nevertheless, Murray *et al.* note there was a reallocation of biomass from aboveground organs (leaves and stems) into roots in the low-nitrogen treatment; and they remark that this phenomenon "may provide a long-term mechanism by which Sitka spruce could utilize limited resources both more efficiently and effectively," which suggests that although low soil nitrogen precluded a short-term CO<sub>2</sub>-induced growth response in this tree species, it is possible that the negative impact of nitrogen deficiency could be overcome in the course of much longer-term atmospheric CO<sub>2</sub> enrichment.

In a related experiment, Liu *et al.* (2002) grew Sitka spruce seedlings in well-watered and fertilized pots within open-top chambers that were maintained for three years at atmospheric CO<sub>2</sub> concentrations of either 350 or 700 ppm, after which the seedlings were planted directly into native nutrient-deficient forest soil and maintained at the same atmospheric CO<sub>2</sub> concentrations for two more years in larger open-top chambers either with or without extra nitrogen being supplied to the soil. After the first three years of the study, they determined that the CO<sub>2</sub>-enriched trees possessed 11.6% more total biomass than the ambient-treatment trees. At the end of the next two years, however, the CO<sub>2</sub>-enriched trees supplied with extra nitrogen had 15.6% more total biomass than their similarly-treated ambient-air counterparts, while the CO<sub>2</sub>-enriched trees receiving no extra nitrogen had 20.5% more biomass than their ambient-treatment counterparts.

In light of these several observations, it would appear that the degree of soil nitrogen availability can indeed alter the aerial fertilization effect of atmospheric CO<sub>2</sub> enrichment on the growth of spruce trees by promoting a greater CO<sub>2</sub>-induced growth enhancement in soils of adequate, as opposed to insufficient, nitrogen content. As in the cases of aspen and pine, however, there is evidence to suggest that at some point the response of spruce trees to increasing soil nitrogen also saturates, and that higher nitrogen concentrations may possibly even reduce the growth response to elevated CO<sub>2</sub> below that observed at optimal or low soil nitrogen concentrations.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/n/nitrogenspruce.php>.

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#### 6.3.7.4.4. OTHER

Maillard *et al.* (2001) grew pedunculate oak seedlings for three to four months in greenhouses maintained at atmospheric CO<sub>2</sub> concentrations of either 350 or 700 ppm under conditions of either low or high soil nitrogen concentration. The elevated CO<sub>2</sub> of their study stimulated belowground growth in the seedlings growing in the nitrogen-poor soil, significantly increasing their root-to-shoot ratios. However, it increased both the below- *and* above-ground biomass of seedlings growing in nitrogen-*rich* soil. In fact, the CO<sub>2</sub>-enriched seedlings growing in the nitrogen-rich soil produced 217 and 533% more stem and coarse-root biomass, respectively, than their ambient-air counterparts growing in the same fertility treatment. Overall, the doubled CO<sub>2</sub> concentration of the air in their study enhanced *total* seedling biomass by approximately 30 and 140% under nitrogen-poor and nitrogen-rich soil conditions, respectively.

Schortemeyer *et al.* (1999) grew seedlings of *Acacia melanoxylon* (a leguminous nitrogen-fixing tree native to south-eastern Australia) in hydroponic culture for six weeks in growth cabinets, where the air was maintained at CO<sub>2</sub> concentrations of either 350 or 700 ppm and the seedlings were supplied with water containing nitrogen in a number of discrete concentrations ranging from 3 to 6,400 mmol m<sup>-3</sup>. In the two lowest of these nitrogen concentration treatments, final biomass was unaffected by atmospheric CO<sub>2</sub> enrichment; but, as in the study of Maillard *et al.*, it was increased by 5- to 10-fold at the highest nitrogen concentration.



Temperton *et al.* (2003) measured total biomass production in another N<sub>2</sub>-fixing tree - *Alnus glutinosa* (the common alder) - seedlings of which had been grown for three years in open-top chambers in either ambient or elevated (ambient + 350 ppm) concentrations of atmospheric CO<sub>2</sub> and one of two soil nitrogen regimes (full nutrient solution or no fertilizer). In their study, by contrast, they found that the trees growing under low soil nutrient conditions exhibited essentially the *same* growth enhancement as that of the well-fertilized trees.

Rounding out the full gamut of growth responses, Gleadow *et al.* (1998) grew eucalyptus seedlings for six months in glasshouses maintained at atmospheric CO<sub>2</sub> concentrations of either 400 or 800 ppm, fertilizing them twice daily with low or high nitrogen solutions. They found that their doubling of the air's CO<sub>2</sub> concentration increased total seedling biomass by 134% in the low nitrogen treatment but by a smaller 98% in the high nitrogen treatment. In addition, the elevated CO<sub>2</sub> led to greater root growth in the low nitrogen treatment, as indicated by a 33% higher root:shoot ratio.

In light of these several results, it is clear that different species of trees may respond in qualitatively different ways to atmospheric CO<sub>2</sub> enrichment in terms of their growth stimulation being greater or smaller under conditions of low vs. high soil nitrogen fertility. In the majority of cases, however, as may be discerned by reviewing the results of similar studies conducted on aspen, pine and spruce trees, the most common response is for the growth-promoting effects of atmospheric CO<sub>2</sub> enrichment to be expressed to a greater degree when soil nitrogen fertility is optimal as opposed to less-than-optimal.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/o/ozonetreemisc.php>.

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### 6.3.8. Salinity Effects

In managed agricultural ecosystems, the buildup of soil salinity from repeated irrigations can sometimes reduce crop yields. Similarly, in natural ecosystems where exposure to brackish or salty water is commonplace, saline soils can induce growth stress in plants not normally adapted to coping with this problem. Thus, it is important to understand how rising atmospheric CO<sub>2</sub> concentrations may interact with soil salinity to affect plant growth.

In the study of Ball *et al.* (1997), it was found that two Australian mangrove species, with differing tolerance to salinity, exhibited increased rates of net photosynthesis in response to a doubling of the atmospheric CO<sub>2</sub> concentration, but only when exposed to salinity levels that were 25%, but not 75%, of full-strength seawater. However, Mavrogianopoulos *et al.* (1999) reported that atmospheric CO<sub>2</sub> concentrations of 800 and 1200 ppm stimulated photosynthesis in parnon melons by 75 and 120%, respectively, regardless of soil salinity, which ranged from 0 to 50 mM NaCl. Moreover, the authors noted that atmospheric CO<sub>2</sub> enrichment partially alleviated the negative effects of salinity on melon yield, which increased with elevated CO<sub>2</sub> at all salinity levels. Furthermore, Maggio *et al.* (2002) grew tomatoes at 400 and 900 ppm in combination with varying degrees of soil salinity and noted that plants grown in elevated CO<sub>2</sub> tolerated an average root-zone salinity threshold value that was about 60% greater than that exhibited by plants grown at 400 ppm CO<sub>2</sub> (51 vs. 32 mmol dm<sup>-3</sup> Cl).

In conclusion, it is clear that elevated CO<sub>2</sub> may alleviate some of the negative impacts of high soil salinity on plant growth. In addition, as indicated in the review of Poorter and Perez-Soba (2001), there appear to be no changes in the effect of elevated CO<sub>2</sub> on the growth responses of most plants over a wide range of soil salinities, in harmony with the earlier findings of Idso and Idso (1994). Hence, plants should respond positively to future increases in the air's CO<sub>2</sub> content, even in areas where mild to moderate stresses may be present due to high soil salinity levels.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/s/salinitystress.php>.

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### 6.3.9. Temperature

As the air's CO<sub>2</sub> content continues to rise, most plants will exhibit increased rates of photosynthesis and biomass production. Consequently, this phenomenon should enhance the amount of food, fiber and timber products that can be used to feed, clothe and shelter earth's expanding human population. However, some climate alarmists have predicted that the growth-promoting effects of atmospheric CO<sub>2</sub> enrichment may be negated by global warming, which could compromise our ability to sustain greater human populations without increasing arable land acreage. We thus turn to the scientific literature to see if plants will continue to exhibit CO<sub>2</sub>-induced growth increases under conditions of elevated air temperature. In this section, we review the photosynthetic and growth responses of agricultural crops, grasslands and woody species within this context.

#### 6.3.9.1. Agricultural Crops

In order to better understand the issues being addressed in this review, one must realize that the optimum growth temperature for several plants has already been shown to rise substantially with increasing levels of atmospheric CO<sub>2</sub> (McMurtrie and Wang, 1993; McMurtrie *et al.*, 1992; Stuhlfauth and Fock, 1990; Berry and Bjorkman, 1980). This phenomenon was predicted by Long (1991), who calculated from well-established plant physiological principles that most C<sub>3</sub> plants should increase their optimum growth temperature by approximately 5°C for a 300 ppm increase in the air's CO<sub>2</sub> content. One would thus also expect plant photosynthetic rates to rise with concomitant increases in the air's CO<sub>2</sub> concentration and temperature, as has indeed been previously shown to be true by Idso and Idso (1994). Hence, we here proceed to see if these positive CO<sub>2</sub> x temperature interactions are still being supported in the recent scientific literature.

In the study of Zhu *et al.* (1999), pineapples grown at 700 ppm CO<sub>2</sub> assimilated 15, 97 and 84% more total carbon than pineapples grown at the current ambient CO<sub>2</sub> concentration in day/night air temperature regimes of 30/20 (which is optimal for pineapple growth at ambient CO<sub>2</sub>), 30/25, and 35/25 °C, respectively. Similarly, Taub *et al.* (2000) demonstrated that net photosynthetic rates of cucumbers grown at twice-ambient levels of atmospheric CO<sub>2</sub> and air temperatures of 40°C were 3.2 times greater than those displayed by control plants grown at ambient CO<sub>2</sub> and this same elevated air temperature. Thus, at air temperatures normally considered to be deleterious to plant growth, rates of photosynthesis are typically considerably greater for CO<sub>2</sub> enriched vs. ambiently-grown plants.

Other studies report similar results. Reddy *et al.* (1999), for example, grew cotton plants at air temperatures ranging from 2°C below to 7°C above ambient air temperatures and reported that

plants simultaneously exposed to 720 ppm CO<sub>2</sub> displayed photosynthetic rates that were 137 to 190% greater than those displayed by plants exposed to ambient CO<sub>2</sub> concentrations across this temperature spectrum. Similarly, Cowling and Sage (1998) reported that a 200-ppm increase in the air's CO<sub>2</sub> concentration boosted photosynthetic rates of young bean plants by 58 and 73% at growth temperatures of 25 and 36°C, respectively. In addition, Bunce (1998) grew wheat and barley at 350 and 700 ppm CO<sub>2</sub> across a wide range of temperatures and reported that elevated CO<sub>2</sub> stimulated photosynthesis in these species by 63 and 74%, respectively, at an air temperature of 10°C and by 115 and 125% at 30°C. Thus, the percentage increase in photosynthetic rate resulting from atmospheric CO<sub>2</sub> enrichment often increases substantially with increasing air temperature.

On another note, elevated CO<sub>2</sub> often aids in the recovery of plants from high temperature-induced reductions in photosynthetic capacity, as noted by Ferris *et al.* (1998), who grew soybeans for 52 days under normal air temperature and soil water conditions at atmospheric CO<sub>2</sub> concentrations of 360 and 700 ppm, but then subjected them to an 8-day period of high temperature and water stress. After normal air temperature and soil water conditions were restored, the CO<sub>2</sub>-enriched plants attained photosynthetic rates that were 72% of their unstressed controls, while stressed plants grown at ambient CO<sub>2</sub> attained photosynthetic rates that were only 52% of their respective controls.

CO<sub>2</sub>-induced increases in plant growth under high air temperatures have also been observed in a number of other agricultural species. In the previously mentioned study of Cowling and Sage (1998), for example, the 200-ppm increase in the air's CO<sub>2</sub> content boosted total plant biomass for wheat and barley by a combined average of 59 and 200% at air temperatures of 25 and 36°C. Similarly, Ziska (1998) reported that a doubling of the atmospheric CO<sub>2</sub> concentration increased the total dry weight of soybeans by 36 and 42% at root zone temperatures of 25 and 30°C, respectively. Likewise, Hakala (1998) noted that spring wheat grown at 700 ppm CO<sub>2</sub> attained total biomass values that were 17 and 23% greater than those attained by ambiently-grown plants exposed to ambient and elevated (ambient plus 3°C) air temperatures. In addition, after inputting various observed CO<sub>2</sub>-induced growth responses of winter wheat into plant growth models, Alexandrov and Hoogenboom (2000) predicted 12 to 49% increases in wheat yield in Bulgaria even if air temperatures rise by as much as 4°C. Finally, in the study of Reddy *et al.* (1998), it was shown that elevated CO<sub>2</sub> (700 ppm) increased total cotton biomass by 31 to 78% across an air temperature range from 20 to 40°C. Thus, the beneficial effects of elevated CO<sub>2</sub> on agricultural crop yield is often enhanced due to elevated air temperature.

In some cases, however, elevated CO<sub>2</sub> does *not* interact with air temperature to further increase the growth-promoting effects of atmospheric CO<sub>2</sub> enrichment, but simply allows the maintenance of the *status quo*. In the study of Demmers-Derks *et al.* (1998), for example, sugar beets grown at 700 ppm CO<sub>2</sub> attained 25% more biomass than ambiently-grown plants, regardless of air temperature, which was increased by 3°C. Similarly, in the study of Fritschi *et al.* (1999), elevated CO<sub>2</sub> concentrations did not significantly interact with air temperature (4.5°C above ambient) to impact the growth of rhizoma peanut. Nonetheless, the 300-ppm increase in the air's CO<sub>2</sub> content increased total biomass by 52%, regardless of air temperature.

Finally, even if the air's CO<sub>2</sub> content were to cease rising or have no effect on plants, it is possible that temperature increases alone would promote plant growth and development. This was the case in the study of Wurr *et al.* (2000), where elevated CO<sub>2</sub> had essentially no effect on the yield of French bean. However, a 4°C increase in air temperature increased yield by approximately 50%.

In conclusion, the recent scientific literature continues to indicate that as the air's CO<sub>2</sub> content continues to rise, agricultural crops will likely exhibit enhanced rates of photosynthesis and biomass production that will not be diminished by any global warming that might occur concurrently. In fact, if the ambient air temperature rises, the growth-promoting effects of atmospheric CO<sub>2</sub> enrichment will likely rise right along with it, becoming more and more robust in agreement with the experimental observations reviewed by Idso and Idso (1994). Thus, the biosphere's ability to continue producing the food and fiber needed to feed and clothe the increasing population of humanity looks good indeed ... as long, that is, as the CO<sub>2</sub> content of the air continues its 350-year habit of rising hand-in-hand with the population of the planet.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/g/tempco2aq.php>.

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#### 6.3.9.2. Grassland Species

In the study of Lilley *et al.* (2001), swards of *Trifolium subterraneum* were grown at 380 and 690 ppm CO<sub>2</sub> in combination with simultaneous exposure to ambient and elevated (ambient plus 3.4°C) air temperature. After one year of treatment, they reported that elevated CO<sub>2</sub> increased foliage growth by 19% at ambient air temperature. At elevated air temperature, however, plants grown at ambient CO<sub>2</sub> exhibited a 28% *reduction* in foliage growth, while CO<sub>2</sub>-enriched plants still displayed a growth *enhancement* of 8%. Similarly, Morgan *et al.* (2001) reported that twice-ambient levels of atmospheric CO<sub>2</sub> increased aboveground biomass in native shortgrass steppe ecosystems by an average of 38%, in spite of an average air temperature increase of 2.6°C. Likewise, when bahiagrass was grown across a temperature gradient of 4.5°C, Fritschi *et al.* (1999) reported that a 275 ppm increase in the air's CO<sub>2</sub> content boosted photosynthesis and aboveground biomass by 22 and 17%, respectively, independent of air temperature. Thus, at elevated air temperature, CO<sub>2</sub>-induced increases in rates of photosynthesis and biomass production are typically equal to or greater than what they are at ambient air temperature.

Other studies report similar results. Greer *et al.* (2000), for example, grew five pasture species at 18 and 28°C and reported that plants concomitantly exposed to 700 ppm CO<sub>2</sub> displayed average photosynthetic rates that were 36 and 70% greater, respectively, than average rates exhibited by control plants subjected to ambient CO<sub>2</sub> concentrations. Moreover, the average CO<sub>2</sub>-induced biomass increase for these five species rose dramatically with increasing air temperature: from only 8% at 18°C to 95% at 28°C. Thus, the beneficial effects of elevated CO<sub>2</sub> on grassland productivity is often significantly enhanced by elevated air temperature.

Finally, even if the air's CO<sub>2</sub> content were to cease rising or have no effect on plants, it is possible that temperature increases alone would promote plant growth and development. This was the case in the study of Norton *et al.* (1999), where elevated CO<sub>2</sub> had essentially no effect on the growth of the perennial grass *Agrostis curtisii* after two years of fumigation. However, a 3°C increase in air temperature increased the growth of this species considerably.

In conclusion, the recent scientific literature continues to indicate that as the air's CO<sub>2</sub> content rises, grassland plants will likely exhibit enhanced rates of photosynthesis and biomass production that will not be diminished by any global warming that might occur concurrently. In fact, if the ambient air temperature does rise, the growth-promoting effects of atmospheric CO<sub>2</sub> enrichment will likely rise right along with it, becoming more and more robust in agreement with the experimental observations reviewed by Idso and Idso (1994). The future ability of grasslands to produce increasingly greater amounts of forage, and perhaps reclaim areas of barren ground in certain environments, thus looks promising indeed, as long as the air's CO<sub>2</sub> content continues to rise.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/g/tempco2grass.php>.

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#### 6.3.9.3. Trees

In the study of Kellomaki and Wang (2001), birch seedlings were grown at atmospheric CO<sub>2</sub> concentrations of 350 and 700 ppm in combination with ambient and elevated (ambient plus 3°C) air temperatures. After five months of treatment, the authors reported that photosynthetic rates of CO<sub>2</sub>-enriched seedlings were 21 and 28% greater than those displayed by their ambiently-grown counterparts at ambient and elevated air temperatures, respectively. In another study, Carter *et al.* (2000) observed that a 300 ppm increase in the air's CO<sub>2</sub> content allowed leaves of sugar maple seedlings to remain green and non-chlorotic when exposed to air temperatures 3°C above ambient air temperature. On the other hand, seedlings fumigated with ambient air exhibited severe foliar chlorosis when exposed to the same elevated air temperatures. These results thus indicate that at elevated air temperatures, rates of photosynthesis are greater and foliar health is typically better in CO<sub>2</sub>-enriched as opposed to ambiently-grown trees.

Other studies report similar results. Sheu *et al.* (1999), for example, grew a sub-tropical tree at day/night temperatures of 25/20 (ambient) and 30/25°C (elevated) for six months and reported that seedlings exposed to 720 ppm CO<sub>2</sub> displayed photosynthetic rates that were 20 and 40% higher, respectively, than that of their ambiently-grown controls. In addition, the CO<sub>2</sub>-induced increases in total dry weight for this species were 14 and 49%, respectively, at ambient and elevated air temperatures. Likewise, Maherali *et al.* (2000) observed that a 5°C increase in ambient air temperature increased the CO<sub>2</sub>-induced biomass enhancement resulting from a 750



ppm CO<sub>2</sub> enrichment of ponderosa pine seedlings from 42 to 62%. Moreover, Wayne *et al.* (1998) reported that a 5°C increase in the optimal growth temperature of yellow birch seedlings fumigated with an extra 400 ppm CO<sub>2</sub> increased the CO<sub>2</sub>-induced increase in biomass from 60 to 227%. Thus, the beneficial effects of elevated CO<sub>2</sub> on tree species photosynthesis and growth is often enhanced due to elevated air temperatures, which can also be assessed during natural seasonal temperature changes, as documented by Hymus *et al.* (1999) for loblolly pine and Roden *et al.* (1999) for snow gum seedlings.

In some cases, however, there appear to be little interactive effects between elevated CO<sub>2</sub> and temperature on photosynthesis and growth in tree species. When Tjoelker *et al.* (1998a), for example, grew seedlings of quaking aspen, paper birch, tamarack, black spruce and jack pine at atmospheric CO<sub>2</sub> concentrations of 580 ppm, they reported average increases in photosynthetic rates of 28%, regardless of temperature, which varied from 18 to 30°C. After analyzing the CO<sub>2</sub>-induced increases in dry mass for these seedlings, Tjoelker *et al.* (1998b) further reported that dry mass values were about 50 and 20% greater for the deciduous and coniferous species, respectively, regardless of air temperature.

In conclusion, the recent scientific literature continues to indicate that as the air's CO<sub>2</sub> content rises, trees will likely exhibit enhanced rates of photosynthesis and biomass production that will not be negated by any global warming that might occur concurrently. In fact, if the ambient air temperature rises, the growth-promoting effects of atmospheric CO<sub>2</sub> enrichment will likely rise right along with it, in agreement with the experimental observations reviewed by Idso and Idso (1994). Thus, the future ability of earth's trees to produce greater amounts of biomass and, hence, more timber products to meet the increasing needs of an expanding human population looks promising indeed, as long as the CO<sub>2</sub> content of the air continues to rise.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/g/tempco2trees.php>.

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#### 6.3.9.4. Other

In a mechanistic model study of Mediterranean shrub vegetation, Osborne *et al.* (2000) reported that increased warming and reduced precipitation would likely decrease net primary production. However, when the same model was run at twice the ambient atmospheric CO<sub>2</sub> concentration, it predicted a 25% increase in vegetative productivity, in spite of the increased warming and reduced precipitation. Although we tend to not review studies based on mechanistic models, it is also interesting to note that Bunce (2000) demonstrated that field-grown *Taraxacum officinale* plants exposed to 525 ppm CO<sub>2</sub> and *low* air temperatures (between 15 and 25°C) displayed photosynthetic rates that were 10 to 30% greater than what was predicted by state-of-the-art biochemical models of photosynthesis for this range of temperatures. Thus, at both high and low air temperatures, elevated CO<sub>2</sub> appears to be capable of significantly increasing the photosynthetic prowess of certain of the native plants of earth's natural ecosystems.

In the real world, Stirling *et al.* (1998) grew five fast-growing native species at various atmospheric CO<sub>2</sub> concentrations and air temperatures, finding that twice-ambient levels of atmospheric CO<sub>2</sub> increased photosynthetic rates by 18-36% for all species regardless of air temperature, which was up to 3°C higher than ambient air temperature. In addition, atmospheric CO<sub>2</sub> enrichment increased average plant biomass by 25%, also regardless of air temperature. Likewise, in a study of vascular plants from Antarctica, Xiong *et al.* (2000) reported that a 13°C rise in air temperature increased plant biomass by 2- to 3-fold. We can only imagine what the added benefit of atmospheric CO<sub>2</sub> enrichment would do for these species!

On another note, Hamerlynck *et al.* (2000) demonstrated that the desert perennial shrub *Larrea tridentata* maintained more favorable midday leaf water potentials during a nine-day high-temperature treatment when fumigated with 700 ppm CO<sub>2</sub>, as compared to 350 ppm, which would likely favor enhanced rates of photosynthesis as well.

In conclusion, the recent scientific literature continues to indicate that as the air's CO<sub>2</sub> content rises, the native plants of earth's natural ecosystems will likely exhibit enhanced rates of photosynthesis and biomass production that will not be diminished by any realistic increase in air temperature. In fact, if the ambient air temperature does rise somewhat, the growth-promoting effects of atmospheric CO<sub>2</sub> enrichment will likely rise right along with it, in agreement with the experimental observations reviewed by Idso and Idso (1994). Thus, the productivity of earth's natural ecosystems will likely continue its upward trend, even in the face of modest global warming, as long as the air's CO<sub>2</sub> content is in an ascending mode as well.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/g/tempco2growthres.php>.

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### 6.3.10. UV-B Radiation

Zhao *et al.* (2004) report that "as a result of stratospheric ozone depletion, UV-B radiation (280-320 nm) levels are still high at the Earth's surface and are projected to increase in the near future (Madronich *et al.*, 1998; McKenzie *et al.*, 2003)." In reference to this potential development, they note that "increased levels of UV-B radiation are known to affect plant growth, development and physiological processes (Dai *et al.*, 1992; Nouges *et al.*, 1999),"

stating that high UV-B levels often result in "inhibition of photosynthesis, degradation of protein and DNA, and increased oxidative stress (Jordan *et al.*, 1992; Stapleton, 1992)." Similar concern has been expressed in the CRDs, but the subject is treated there only lightly. In light of the above observations, it is important to clarify for the EPA's endangerment ruling how the ongoing rise in the air's CO<sub>2</sub> content might impact the deleterious effects of UV-B radiation on earth's vegetation.

To investigate this question, Zhao *et al.* grew well watered and fertilized cotton plants in sunlit controlled environment chambers maintained at atmospheric CO<sub>2</sub> concentrations of 360 or 720 ppm from emergence until three weeks past first-flower stage under three levels of UV-B radiation (0, 8 and 16 kJ m<sup>-2</sup> d<sup>-1</sup>); and on five dates between 21 and 62 days after emergence, they measured a number of plant physiological processes and parameters. Over the course of the experiment, the mean net photosynthetic rate of the upper-canopy leaves in the CO<sub>2</sub>-enriched chambers was increased -- relative to that in the ambient-air chambers -- by 38.3% in the low UV-B treatment (from 30.3 to 41.9 m m<sup>-2</sup> s<sup>-1</sup>), 41.1% in the medium UV-B treatment (from 28.7 to 40.5 m m<sup>-2</sup> s<sup>-1</sup>), and 51.5% in the high UV-B treatment (from 17.1 to 25.9 m m<sup>-2</sup> s<sup>-1</sup>). In the medium UV-B treatment, the growth stimulation from the elevated CO<sub>2</sub> was sufficient to raise net photosynthesis rates 33.7% above the rates experienced in the ambient air and no UV-B treatment (from 30.3 to 40.5 m m<sup>-2</sup> s<sup>-1</sup>); but in the high UV-B treatment the radiation damage was so great that even with the help of the 51.5% increase in net photosynthesis provided by the doubled-CO<sub>2</sub> air, the mean net photosynthesis rate of the cotton leaves was 14.5% less than that experienced in the ambient air and no UV-B treatment (dropping from 30.3 to 25.9 m m<sup>-2</sup> s<sup>-1</sup>).

It should be noted, however, that the medium UV-B treatment of this study was chosen to represent the intensity of UV-B radiation presently received on a clear summer day in the major cotton production region of Mississippi, USA, under current stratospheric ozone conditions, while the high UV-B treatment was chosen to represent what might be expected there following a 30% depletion of the ozone layer, which has been predicted to double the region's reception of UV-B radiation from 8 to 16 kJ m<sup>-2</sup> d<sup>-1</sup>. Consequently, a doubling of the current CO<sub>2</sub> concentration and the current UV-B radiation level would reduce the net photosynthetic rate of cotton leaves by just under 10% (from 28.7 to 25.9 m m<sup>-2</sup> s<sup>-1</sup>), whereas in the absence of a doubling of the air's CO<sub>2</sub> content, a doubling of the UV-B radiation level would reduce cotton net photosynthesis by just over 40% (from 28.7 to 17.1 m m<sup>-2</sup> s<sup>-1</sup>).

Viewed in this light, it can be seen that a doubling the current atmospheric CO<sub>2</sub> concentration would compensate for over three-fourths of the loss of cotton photosynthetic capacity caused by a doubling of the current UV-B radiation intensity; and it may possibly do even better than that, for in the study of Zhao *et al.* (2003), it was reported that both Adamse and Britz (1992) and Rozema *et al.* (1997) found that doubled CO<sub>2</sub> totally compensated for the negative effects of equally high UV-B radiation.

In another study (Qaderi and Reid, 2005), well watered and fertilized plants were grown from seed to maturity in pots within controlled environment chambers maintained at either 370 or

740 ppm CO<sub>2</sub> with and without a daily dose of UV-B radiation in the amount of 4.2 kJ m<sup>-2</sup>, while a number of plant parameters were measured at various times throughout the growing season. With respect to the bottom-line result of *final seed yield*, this parameter was determined to be 0.98 g/plant in the control treatment (ambient CO<sub>2</sub>, with UV-B). Doubling the CO<sub>2</sub> concentration increased yield by 25.5% to 1.23 g/plant. Alternatively, removing the UV-B radiation flux increased yield by 91.8% to 1.88 g/plant. Doing both (doubling the CO<sub>2</sub> concentration while simultaneously removing the UV-B flux) increased final seed yield most of all, by 175.5% to 2.7 g/plant. Viewed from a different perspective, doubling the air's CO<sub>2</sub> concentration in the *presence* of the UV-B radiation flux enhanced final seed yield by 25.5%, while doubling CO<sub>2</sub> in the *absence* of the UV-B radiation flux increased seed yield by 43.6%. In concluding their paper, the authors note that "previous studies have shown that elevated CO<sub>2</sub> increases biomass and seed yield, whereas UV-B decreases them (Sullivan, 1997; Teramura *et al.*, 1990)." Finding much the same thing in their study, they thus reckoned that "elevated CO<sub>2</sub> may have a positive effect on plants by mitigating the detrimental effects caused by UV-B radiation."

Two years later in a similar study of the same plant, Qaderi *et al.* (2007) grew well watered and fertilized canola (*Brassica napus* L.) plants from the 30-day-old stage until 25 days after anthesis in 1-L pots within controlled environment chambers exposed to either 4.2 kJ m<sup>-2</sup> d<sup>-1</sup> of UVB radiation or no such radiation in air of either 370 or 740 ppm CO<sub>2</sub>, in order to determine the effects of these two parameters on the photosynthetic rates and water use efficiency of the maturing husks or *siliquas* that surround the plants' seeds. Results indicated that for the plants exposed to 4.2 kJ m<sup>-2</sup> d<sup>-1</sup> of UVB radiation, the experimental doubling of the air's CO<sub>2</sub> concentration led to a 29% increase in siliqua net photosynthesis, an 18% decrease in siliqua transpiration, and a 58% increase in siliqua water use efficiency; while for the plants exposed to *no* UVB radiation, siliqua net photosynthesis was increased by a *larger* 38%, transpiration was decreased by a *larger* 22% and water use efficiency was increased by a *larger* 87% in the CO<sub>2</sub>-enriched air.

Although UV-B radiation levels are projected to increase in the near future as a result of stratospheric ozone depletion, in the slightly more distant future, however, when stratospheric ozone levels are projected to decline as a result of the worldwide ban on stratospheric-ozone-depleting substances, the biologically-beneficial effects of the ongoing rise in the air's CO<sub>2</sub> content will likely become *ever greater* as UVB levels at the earth's surface begin their anticipated long-term decline. As a result, the long-term agricultural and biospheric benefits of atmospheric CO<sub>2</sub> enrichment may well be significantly greater than what has been suggested by past and current open-top chamber and FACE experiments.

In another noteworthy study, Deckmyn *et al.* (2001) grew white clover plants for four months in four small greenhouses, two of which allowed 88% of the incoming UV-B radiation to pass through their roofs and walls and two of which allowed 82% to pass through, while one of the two greenhouses in each of the UV-B treatments was maintained at ambient CO<sub>2</sub> (371 ppm) and the other at elevated CO<sub>2</sub> (521 ppm). At the mid-season point of their study, they found that the 40% increase in atmospheric CO<sub>2</sub> concentration stimulated the production of flowers in

the low UV-B treatment by 22% and in the slightly higher UV-B treatment by 43%; while at the end of the season, the extra CO<sub>2</sub> was determined to have provided no stimulation of biomass production in the low UV-B treatment, but it significantly stimulated biomass production by 16% in the high UV-B treatment.

The results of this study indicate that the positive effects of atmospheric CO<sub>2</sub> enrichment on flower and biomass production in white clover are greater at more realistic or natural values of UV-B radiation than those found in many greenhouses. As a result, Deckmyn *et al.* say their results "clearly indicate the importance of using UV-B transmittant greenhouses or open-top chambers when conducting CO<sub>2</sub> studies," for if this is not done, their work suggests that the results obtained could significantly underestimate the magnitude of the benefits that are being continuously accrued by earth's vegetation as a result of the ongoing rise in the air's CO<sub>2</sub> content.

The interactive effects of CO<sub>2</sub> and UV-B radiation has also been the subject of analysis. In 2007, Koti *et al.* (2007) used Soil-Plant-Atmosphere-Research (SPAR) chambers at Mississippi State University (USA) to investigate the effects of doubled atmospheric CO<sub>2</sub> concentration (720 vs. 360 ppm) on the growth and development of six well watered and fertilized soybean (*Glycine max* L.) genotypes grown from seed in pots filled with fine sand and exposed to the dual stresses of high day/night temperatures (38/30°C vs. 30/22°C) and high UV-B radiation levels (10 vs. 0 kJ/m<sup>2</sup>/day). Results led this group of authors to report that "elevated CO<sub>2</sub> partially compensated [for] the damaging effects on vegetative growth and physiology caused by negative stressors such as high temperatures and enhanced UV-B radiation levels in soybean," specifically noting, in this regard, CO<sub>2</sub>'s positive influence on the physiological parameters of plant height, leaf area, total biomass, net photosynthesis, total chlorophyll content, phenolic content and wax content, as well as relative plant injury.

In a study that did not include UV-B radiation as an experimental parameter, Estiarte *et al.* (1999) grew spring wheat in FACE plots in Arizona, USA, at atmospheric CO<sub>2</sub> concentrations of 370 and 550 ppm and two levels of soil moisture (50 and 100% of potential evapotranspiration). They found that leaves of plants grown in elevated CO<sub>2</sub> had 14% higher total flavonoid concentrations than those of plants grown in ambient air, and that soil water content did not affect the relationship. An important aspect of this finding is that one of the functions of flavonoids in plant leaves is to protect them against UV-B radiation. More studies of this nature should thus be conducted to see how general this beneficial response may be throughout the plant world.

In a study of UV-B and CO<sub>2</sub> effects on a *natural* ecosystem, which was conducted at the Abisko Scientific Research Station in Swedish Lapland, Johnson *et al.* (2002) studied plots of subarctic heath composed of open canopies of downy birch and dense dwarf-shrub layers containing scattered herbs and grasses. For a period of five years, they exposed the plots to factorial combinations of UV-B radiation -- ambient and that expected to result from a 15% stratospheric ozone depletion -- and atmospheric CO<sub>2</sub> concentration -- ambient (around 365 ppm) and

enriched (around 600 ppm) -- after which they determined the amounts of microbial carbon ( $C_{mic}$ ) and nitrogen ( $N_{mic}$ ) in the soils of the plots.

When the plots were exposed to the enhanced UV-B radiation, the amount of  $C_{mic}$  in the soil was reduced to only 37% of what it was at the ambient UV-B level when the air's  $CO_2$  content was maintained at the ambient concentration. When the UV-B increase was accompanied by the  $CO_2$  increase, however, not only was there *not* a decrease in  $C_{mic}$ , there was an actual *increase* of 37%. The story with respect to  $N_{mic}$  was both similar and different at one and the same time. In this case, when the plots were exposed to the enhanced level of UV-B radiation, the amount of  $N_{mic}$  in the soil experienced a 69% *increase* when the air's  $CO_2$  content was maintained at the ambient concentration; and when the UV-B increase was accompanied by the  $CO_2$  increase,  $N_{mic}$  rose even more, by a whopping 138%.

These findings, in the words of Johnson *et al.*, "may have far-reaching implications ... because the productivity of many semi-natural ecosystems is limited by N (Ellenberg, 1988)." Hence, the 138% increase in soil microbial N observed in this study to accompany a 15% reduction in stratospheric ozone and a 64% increase in atmospheric  $CO_2$  concentration (experienced in going from 365 ppm to 600 ppm) should significantly enhance the input of plant litter to the soils of these ecosystems, which phenomenon represents the first half of the carbon sequestration process, i.e., the carbon input stage. With respect to the second stage of *keeping* as much of that carbon as possible in the soil, Johnson *et al.* note that "the capacity for subarctic semi-natural heaths to act as major sinks for fossil fuel-derived carbon dioxide is [also] likely to be critically dependent on the supply of N," as is indeed indicated to be the case in the literature review of Berg and Matzner (1997), who report that with more nitrogen in the soil, the long-term storage of carbon is significantly enhanced, as more litter is chemically transformed into humic substances when nitrogen is more readily available, and these more recalcitrant carbon compounds can be successfully stored in the soil for many millennia.

In light of these several findings, we conclude that the ongoing rise in the air's  $CO_2$  content is a powerful antidote for the deleterious biological impacts that might possibly be caused by an increase in the flux of UV-B radiation at the surface of the earth due to any further depletion of the planet's stratospheric ozone layer.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/u/uvradiation.php>.

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### 6.3.11. Water Stress

As the CO<sub>2</sub> content of the air continues to rise, nearly all of earth's plants will exhibit increases in photosynthesis and biomass production; but climate alarmists periodically claim that water stress will negate these benefits. In reviewing the scientific literature of the ten-year period 1983-1994, however, Idso and Idso (1994) found that water stress typically will *not* negate the CO<sub>2</sub>-induced stimulation of plant productivity. In fact, they found that the CO<sub>2</sub>-induced *percentage* increase in plant biomass production was often *greater* under water-stressed conditions than it was when plants were well-watered. We here review some more recent scientific literature in this area for agricultural, grassland and woody plant species.

#### 6.3.11.1. Agricultural Species

During times of water stress, atmospheric CO<sub>2</sub> enrichment often stimulates plants to develop larger-than-usual and more robust root systems to probe greater volumes of soil for scarce and much-needed moisture. Wechsung *et al.* (1999), for example, observed a 70% increase in lateral root dry weights of water-stressed wheat grown at 550 ppm CO<sub>2</sub>, while De Luis *et al.* (1999) reported a 269% increase in root-to-shoot ratio of water-stressed alfalfa growing at 700 ppm CO<sub>2</sub>. Thus, elevated CO<sub>2</sub> elicits stronger-than-usual positive root responses in agricultural species under conditions of water stress.

Elevated levels of atmospheric CO<sub>2</sub> also tend to reduce the openness of stomatal pores on leaves, thus decreasing plant stomatal conductance. This phenomenon, in turn, reduces the amount of water lost to the atmosphere by transpiration and, consequently, lowers overall plant water use. Indeed, Serraj *et al.* (1999) report that water-stressed soybeans grown at 700 ppm CO<sub>2</sub> reduced their total seasonal water loss by 10% relative to that of water-stressed control plants grown at 360 ppm CO<sub>2</sub>. In addition, Conley *et al.* (2001) noted that a 200-ppm increase in the air's CO<sub>2</sub> concentration reduced cumulative evapotranspiration in water-stressed sorghum by approximately 4%.

Atmospheric CO<sub>2</sub> enrichment thus increases plant water *acquisition*, by stimulating root growth, while it reduces plant water *loss*, by constricting stomatal apertures; and these dual effects typically enhance plant water-use efficiency, even under conditions of less-than-optimal soil water content. But these phenomena have other implications as well.

CO<sub>2</sub>-induced increases in root development together with CO<sub>2</sub>-induced reductions in stomatal conductance often contribute to the maintenance of a more favorable plant water status during times of drought. Sgherri *et al.* (1998), for example, have reported that leaf water potential, which is a good indicator of overall plant water status, was 30% higher (less negative and therefore more favorable) in water-stressed alfalfa grown at an atmospheric CO<sub>2</sub> concentration of 600 ppm CO<sub>2</sub> versus 340 ppm CO<sub>2</sub>. In addition, Wall (2001) reports that leaf water potentials were similar in CO<sub>2</sub>-enriched water-stressed plants and ambiently-grown well-watered control plants, which implies a complete CO<sub>2</sub>-induced amelioration of water stress in the CO<sub>2</sub>-enriched plants. Similarly, Lin and Wang (2002) demonstrated that elevated CO<sub>2</sub> caused a several-day delay in the onset of the water stress-induced production of the highly reactive oxygenated compound H<sub>2</sub>O<sub>2</sub> in spring wheat.

If atmospheric CO<sub>2</sub> enrichment thus allows plants to maintain a better water status during times of water stress, it is only logical to expect that such plants should exhibit greater rates of photosynthesis than ambiently-grown plants. And so they do. With the onset of water stress in *Brassica juncea*, for example, photosynthetic rates dropped by 40% in plants growing in ambient air, while plants growing in air containing 600 ppm CO<sub>2</sub> only experienced a 30% reduction in net photosynthesis (Rabha and Uprety, 1998). In another manifestation of this phenomenon, Ferris *et al.* (1998) reported that after imposing water-stress conditions on soybeans and allowing them to recover following complete rewetting of the soil, plants grown in air containing 700 ppm CO<sub>2</sub> reached pre-stressed rates of photosynthesis after six days, while plants grown in ambient air *never* recovered to pre-stressed rates.

Reasoning analogously, it is also only to be expected that plant biomass production would be enhanced by elevated CO<sub>2</sub> concentrations under drought conditions. In exploring this idea, Ferris *et al.* (1999) reported that water-stressed soybeans grown at 700 ppm CO<sub>2</sub> attained seed yields that were 24% greater than those of similarly water-stressed plants grown at ambient CO<sub>2</sub> concentrations, while Hudak *et al.* (1999) reported that water-stress had no effect on yield in CO<sub>2</sub>-enriched spring wheat.

In some cases, the CO<sub>2</sub>-induced *percentage* biomass increase is actually *greater* for water-stressed plants than it is for well-watered plants. Li *et al.* (2000), for example, reported that a 180-ppm increase in the air's CO<sub>2</sub> content increased lower stem grain weights in water-stressed and well-watered spring wheat by 24 and 14%, respectively. Similarly, spring wheat grown in air containing an additional 280 ppm CO<sub>2</sub> exhibited 57 and 40% increases in grain yield under water-stressed and well-watered conditions, respectively (Schutz and Fangmeier, 2001). Likewise, Ottman *et al.* (2001) noted that elevated CO<sub>2</sub> increased plant biomass in water-stressed sorghum by 15%, while no biomass increase occurred in well-watered sorghum.

In summary, the conclusions of Idso and Idso (1994) are well supported by the recent peer-reviewed scientific literature, which indicates that the ongoing rise in the air's CO<sub>2</sub> content will likely lead to substantial increases in plant photosynthetic rates and biomass production, even in the face of stressful conditions imposed by less-than-optimum soil moisture conditions. Indeed, in predicting maize and winter wheat yields in Bulgaria under increased air temperature and decreased precipitation scenarios, Alexandrov and Hoogenboom (2000) noted that yield losses were likely to occur if the atmospheric CO<sub>2</sub> concentration remained unchanged. However, if the atmospheric CO<sub>2</sub> concentration doubled, then maize and winter wheat yields would likely increase even under the stresses of elevated temperature and reduced rainfall. Thus, future increases in the air's CO<sub>2</sub> content will likely lead to increased crop growth and yield production, even in areas where reduced soil moisture availability leads to plant water stress.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/g/growthwateraq.php>.

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#### 6.3.11.2. Grassland Species

Elevated levels of atmospheric CO<sub>2</sub> tend to reduce the area of open stomatal pore space on leaf surfaces, thus reducing plant stomatal conductance. This phenomenon, in turn, effectively reduces the amount of water lost to the atmosphere via transpiration. In the study of Leymarie

*et al.* (1999), for example, twice-ambient levels of atmospheric CO<sub>2</sub> caused significant reductions in the stomatal conductance of water-stressed *Arabidopsis thaliana*. Similarly, Volk *et al.* (2000) reported that calcareous grassland species exposed to elevated CO<sub>2</sub> concentrations (600 ppm) consistently exhibited reduced stomatal conductance, regardless of soil moisture availability. Thus, atmospheric CO<sub>2</sub> enrichment clearly reduces stomatal conductance and, hence, plant transpiration and soil water depletion in grassland ecosystems.

CO<sub>2</sub>-induced increases in root development together with CO<sub>2</sub>-induced reductions in stomatal conductance often combine to maintain a more favorable plant water status during times of drought. In the case of four grassland species comprising a pasture characteristic of New Zealand, for example, Clark *et al.* (1999) found that leaf water potential, which is a good indicator of plant water status, was consistently higher (less negative and, therefore, less stressful) under elevated atmospheric CO<sub>2</sub> concentrations. Similarly, leaf water potentials of the water-stressed C<sub>4</sub> grass *Panicum coloratum* grown at 1000 ppm CO<sub>2</sub> were always higher than those of their water-stressed counterparts growing in ambient air (Seneweera *et al.*, 2001). Indeed, Seneweera *et al.* (1998) reported that leaf water potentials observed in CO<sub>2</sub>-enriched water-stressed plants were an amazing three-and-a-half times greater than those observed in control plants grown at 350 ppm during drought conditions (Seneweera *et al.*, 1998).

If atmospheric CO<sub>2</sub> enrichment thus allows plants to maintain improved water status during times of water stress, it is only logical to expect that such plants will exhibit greater photosynthetic rates than similar plants growing in ambient air. In a severe test of this concept, Ward *et al.* (1999) found that extreme water stress caused 93 and 85% reductions in the photosynthetic rates of two CO<sub>2</sub>-enriched grassland species; yet their rates of carbon fixation were still greater than those observed under ambient CO<sub>2</sub> conditions.

In view of the fact that elevated CO<sub>2</sub> enhances photosynthetic rates during times of water stress, one would expect that plant biomass production would also be enhanced by elevated CO<sub>2</sub> concentrations under drought conditions. And so it is. On the American prairie, for example, Owensby *et al.* (1999) reported that tallgrass ecosystems exposed to twice-ambient concentrations of atmospheric CO<sub>2</sub> for eight years only exhibited significant increases in above- and below-ground biomass during years of less-than-average rainfall. Also, in the study of Derner *et al.* (2001), the authors reported that a 150-ppm increase in the CO<sub>2</sub> content of the air increased shoot biomass in two C<sub>4</sub> grasses by 57%, regardless of soil water content. Moreover, Seneweera *et al.* (2001) reported that a 640-ppm increase in the air's CO<sub>2</sub> content increased shoot dry mass in a C<sub>4</sub> grass by 44 and 70% under well-watered and water-stressed conditions, respectively. Likewise, Volk *et al.* (2000) grew calcareous grassland assemblages at 360 and 600 ppm CO<sub>2</sub> and documented 18 and 40% CO<sub>2</sub>-induced increases in whole-community biomass under well-watered and water-stressed conditions, respectively.

In summary, the peer-reviewed scientific literature indicates that the ongoing rise in the air's CO<sub>2</sub> content will likely lead to substantial increases in plant photosynthetic rates and biomass

production for grassland species, even in the face of stressful environmental conditions imposed by less-than-optimum soil moisture contents.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/g/growthwatergrass.php>.

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#### 6.3.11.3. Woody Species

During times of water stress, atmospheric CO<sub>2</sub> enrichment often stimulates the development of larger-than-usual and more robust root systems in woody perennial species, which allows them to probe greater volumes of soil for scarce and much-needed moisture. Tomlinson and

Anderson (1998), for example, report that greater root development in water-stressed red oak seedlings grown at 700 ppm CO<sub>2</sub> helped them effectively deal with the reduced availability of moisture; and these trees eventually produced just as much biomass as well-watered controls exposed to ambient air containing 400 ppm CO<sub>2</sub>. In addition, Polley *et al.* (1999) note that water-stressed honey mesquite trees subjected to an atmospheric CO<sub>2</sub> concentration of 700 ppm produced 37% more root biomass than water-stressed control seedlings growing at 370 ppm.

Elevated levels of atmospheric CO<sub>2</sub> also tend to reduce the area of open stomatal pore space on leaf surfaces, thus reducing plant stomatal conductance. This phenomenon, in turn, reduces the amount of water lost to the atmosphere via transpiration. Tognetti *et al.* (1998), for example, determined that stomatal conductances of mature oak trees growing near natural CO<sub>2</sub> springs in central Italy were significantly lower than those of similar trees growing further away from the springs during periods of severe summer drought.

CO<sub>2</sub>-induced increases in root development together with CO<sub>2</sub>-induced reductions in stomatal conductance often contribute to the maintenance of a more favorable plant water status during times of drought. In the case of three Mediterranean shrubs, Tognetti *et al.* (2002) found that leaf water potential, which is a good indicator of plant water status, was consistently higher (less negative and, hence, less stressful) under twice-ambient CO<sub>2</sub> concentrations. Similarly, leaf water potentials of water-stressed mesquite seedlings grown at 700 ppm CO<sub>2</sub> were 40% higher than those of their water-stressed counterparts growing in ambient air (Polley *et al.*, 1999), which is comparable to values of -5.9 and -3.4 MPa observed in water-stressed evergreen shrubs (*Larrea tridentata*) exposed to 360 and 700 ppm CO<sub>2</sub>, respectively (Hamerlynck *et al.*, 2000).

If atmospheric CO<sub>2</sub> enrichment thus allows plants to maintain better water status during times of water stress, it is only logical to expect that plants will exhibit CO<sub>2</sub>-induced increases in photosynthesis, even under conditions of low soil moisture availability. It is not surprising, therefore, that Palanisamy (1999) observed water-stressed *Eucalyptus* seedlings grown at 800 ppm CO<sub>2</sub> to display greater net photosynthetic rates than their ambiently-grown and water-stressed counterparts. In fact, Runion *et al.* (1999) observed the CO<sub>2</sub>-induced photosynthetic stimulation of water-stressed pine seedlings grown at 730 ppm CO<sub>2</sub> to be nearly 50% greater than that of similar water-stressed pine seedlings grown at 365 ppm CO<sub>2</sub>. Similarly, Centritto *et al.* (1999a) found that water-stressed cherry trees grown at 700 ppm CO<sub>2</sub> displayed net photosynthetic rates that were 44% greater than those of water-stressed trees grown at 350 ppm CO<sub>2</sub>. And Anderson and Tomlinson (1998) found that a 300-ppm increase in the air's CO<sub>2</sub> concentration boosted photosynthetic rates in well-watered and water-stressed red oak seedlings by 34 and 69%, respectively, demonstrating that the CO<sub>2</sub>-induced percentage enhancement in net photosynthesis in this species was essentially twice as great in water-stressed seedlings as in well-watered ones.

Sometimes, plants suffer drastically when subjected to extreme water stress. However, the addition of CO<sub>2</sub> to the atmosphere often gives them an edge over ambiently-growing plants.

Tuba *et al.* (1998), for example, reported that leaves of a water-stressed woody shrub exposed to an atmospheric CO<sub>2</sub> concentration of 700 ppm continued to maintain positive rates of net carbon fixation for a period that lasted three times longer than that observed for leaves of equally-water-stressed control plants growing in ambient air. Similarly, Fernandez *et al.* (1998) discovered that herb and tree species growing near natural CO<sub>2</sub> vents in Venezuela continued to maintain positive rates of net photosynthesis during that location's dry season, while the same species growing some distance away from the CO<sub>2</sub> source displayed net *losses* of carbon during this stressful time. Likewise, Fernandez *et al.* (1999) noted that after four weeks of drought, the deciduous Venezuelan shrub *Ipomoea carnea* continued to exhibit positive carbon *gains* under elevated CO<sub>2</sub> conditions, whereas ambiently-growing plants displayed net carbon *losses*. In addition, Polley *et al.* (2002) reported that seedlings of five woody species grown at twice-ambient CO<sub>2</sub> concentrations survived 11 days longer (on average) than control seedlings when subjected to maximum drought conditions. Thus, in some cases of water stress, enriching the air with CO<sub>2</sub> can actually mean the difference between a plant's growing or not growing. And if such conditions persist too long, that difference may translate into an actual life-or-death difference.

In view of the fact that elevated CO<sub>2</sub> thus enhances photosynthetic rates during times of water stress, one would expect that plant biomass production would also be enhanced by elevated CO<sub>2</sub> concentrations under drought conditions; and so it is, as demonstrated by Arp *et al.* (1998), who reported that six perennial plants common to the Netherlands increased their biomass under CO<sub>2</sub>-enriched conditions even when suffering from lack of water. In other cases, the CO<sub>2</sub>-induced percentage biomass increase is sometimes even greater for water-stressed plants than it is for well-watered plants. Catovsky and Bazzaz (1999), for example, reported that the CO<sub>2</sub>-induced biomass increase for paper birch was 27% and 130% for well-watered and water-stressed seedlings, respectively. Similarly, Schulte *et al.* (1998) noted that the CO<sub>2</sub>-induced biomass increase of oak seedlings was greater under water-limiting conditions than under well-watered conditions (128% vs. 92%), as did Centritto *et al.* (1999b) for basal trunk area in cherry seedlings (69% vs. 22%).

Finally, Knapp *et al.* (2001) developed tree-ring index chronologies from western juniper stands in Oregon, USA, finding that the trees recovered better from the effects of drought in the 1990's, when the air's CO<sub>2</sub> concentration was around 340 ppm, than they did from 1900-1930, when the atmospheric CO<sub>2</sub> concentration was around 300 ppm. In a loosely related study, Osborne *et al.* (2002) looked at the warming and reduced precipitation experienced in Mediterranean shrublands over the last century and concluded that primary productivity should have been negatively impacted in those areas. However, when the concurrent increase in atmospheric CO<sub>2</sub> concentration was factored into their mechanistic model, a 25% *increase* in primary productivity was projected.

In summary, the peer-reviewed scientific literature indicates that the ongoing rise in the air's CO<sub>2</sub> content will likely lead to substantial increases in photosynthetic rates and biomass production in earth's woody species in the years and decades ahead, even in the face of stressful conditions imposed by less-than-optimal availability of soil moisture.



Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/g/growthwaterwood.php>.

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#### **6.4. Acclimation**

Plants grown in elevated CO<sub>2</sub> environments often exhibit some degree of photosynthetic *acclimation* or *down regulation*, which is typically characterized by long-term rates of photosynthesis that are somewhat lower than what would be expected on the basis of measurements made during short-term exposure to CO<sub>2</sub>-enriched air. These downward

adjustments result from modest long-term decreases in the activities and/or amounts of the primary plant carboxylating enzyme *rubisco*. Acclimation is said to be present when the photosynthetic rates of long-term CO<sub>2</sub>-enriched plants are found to be lower than those of long-term *non*-CO<sub>2</sub>-enriched plants when the normally CO<sub>2</sub>-enriched plants are measured during brief exposures to ambient CO<sub>2</sub> concentrations. Nevertheless, rates of photosynthesis displayed by plants grown and measured at elevated CO<sub>2</sub> concentrations are often greater than those exhibited by plants grown and measured at ambient CO<sub>2</sub> concentrations, leading to enhanced growth in CO<sub>2</sub>-enriched air. In this section, we review research that has been published on acclimation in agricultural, desert, grassland and woody species.

Additional information on this topic, including reviews on acclimation not discussed here, can be found at [http://www.co2science.org/subject/a/subject\\_a.php](http://www.co2science.org/subject/a/subject_a.php) under the heading Acclimation.

#### 6.4.1. Agricultural Species

Several studies have examined the effects of elevated CO<sub>2</sub> on acclimation in agricultural crops. Ziska (1998), for example, reported that soybeans grown at an atmospheric CO<sub>2</sub> concentration of 720 ppm initially exhibited photosynthetic rates that were 50% greater than those observed in control plants grown at 360 ppm. However, after the onset of photosynthetic acclimation, CO<sub>2</sub>-enriched plants displayed subsequent photosynthetic rates that were only 30% greater than their ambiently-grown counterparts. In another study, Theobald *et al.* (1998) grew spring wheat at twice-ambient atmospheric CO<sub>2</sub> concentrations and determined that elevated CO<sub>2</sub> reduced the amount of rubisco required to sustain enhanced rates of photosynthesis, which led to a significant increase in plant photosynthetic nitrogen-use efficiency. CO<sub>2</sub>-induced increases in photosynthetic nitrogen-use efficiency have also been reported in spring wheat by Osborne *et al.* (1998).

In an interesting study incorporating both hydroponically- and pot-grown wheat plants, Farage *et al.* (1998) demonstrated that low nitrogen fertilization does *not* lead to photosynthetic acclimation in elevated CO<sub>2</sub> environments, *as long as the nitrogen supply keeps pace with the relative growth rate of the plants*. Indeed, when spring wheat was grown at an atmospheric CO<sub>2</sub> concentration of 550 ppm in a FACE experiment with optimal soil nutrition and unlimited rooting volume, Garcia *et al.* (1998) could find no evidence of photosynthetic acclimation.

CO<sub>2</sub>-induced photosynthetic acclimation often results from insufficient plant sink strength, which can lead to carbohydrate accumulation in source leaves and the triggering of photosynthetic end product feedback inhibition, which reduces net photosynthetic rates. Indeed, Gesch *et al.* (1998) reported that rice plants -- which have relatively limited potential for developing additional carbon sinks -- grown at an atmospheric CO<sub>2</sub> concentration of 700 ppm exhibited increased leaf carbohydrate contents, which likely reduced *rbcS* mRNA levels and ultimately rubisco protein content. Similarly, Sims *et al.* (1998) reported that photosynthetic acclimation was induced in CO<sub>2</sub>-enriched soybean plants from the significant accumulation of nonstructural carbohydrates in their leaves. However, in growing several

different *Brassica* species at 1,000 ppm CO<sub>2</sub>, Reekie *et al.* (1998) demonstrated that CO<sub>2</sub>-induced acclimation was avoided in species having well-developed carbon sinks (broccoli and cauliflower) and only appeared in those lacking significant sink strength (rape and mustard). Thus, acclimation does not appear to be a direct consequence of atmospheric CO<sub>2</sub> enrichment but rather an indirect effect of low sink strength, which results in leaf carbohydrate accumulation that can trigger acclimation.

In some cases, plants can effectively increase their sink strength, and thus reduce the magnitude of CO<sub>2</sub>-induced acclimation, by forming symbiotic relationships with certain species of soil fungi. Under such conditions, photosynthetic down regulation is not triggered as rapidly, or as frequently, by end product feedback inhibition, as excess carbohydrates are mobilized out of source leaves and sent belowground to symbiotic fungi. Indeed, Louche-Tessandier *et al.* (1999) report that photosynthetic acclimation in CO<sub>2</sub>-enriched potatoes was less apparent when plants were simultaneously colonized by a mycorrhizal fungus. Thus, CO<sub>2</sub>-induced acclimation appears to be closely related to the source:sink balance that exists within plants, being triggered when sink strength falls below, and source strength rises above, critical thresholds in a species-dependent manner.

Acclimation is generally regarded as a process that reduces the amount of rubisco and/or other photosynthetic proteins, which effectively increases the amount of nitrogen available for enhancing sink development or stimulating other nutrient-limited processes. In the study of Watling *et al.* (2000), for example, the authors reported a 50% CO<sub>2</sub>-induced reduction in the concentration of PEP-carboxylase, the primary carboxylating enzyme in C<sub>4</sub> plants, within sorghum leaves. Similarly, Maroco *et al.* (1999) documented CO<sub>2</sub>-induced decreases in both PEP-carboxylase and rubisco in leaves of the C<sub>4</sub> crop maize.

In some cases, however, acclimation to elevated CO<sub>2</sub> is manifested by an "up-regulation" of certain enzymes. When Gesch *et al.* (2002) took rice plants from ambient air and placed them in air containing 700 ppm, for example, they noticed a significant increase in the activity of sucrose-phosphate synthase (SPS), which is a key enzyme involved in the production of sucrose. Similarly, Hussain *et al.* (1999) reported that rice plants grown at an atmospheric CO<sub>2</sub> concentration of 660 ppm displayed 20% more SPS activity during the growing season than did ambiently-grown rice plants. Such increases in the activity of this enzyme could allow CO<sub>2</sub>-enriched plants to avoid the onset of photosynthetic acclimation by synthesizing and subsequently exporting sucrose from source leaves into sink tissues before they accumulate and trigger end product feedback inhibition.

In an interesting experiment, Gesch *et al.* (2000) took ambiently-growing rice plants and placed them in an atmospheric CO<sub>2</sub> concentration of 175 ppm, which reduced photosynthetic rates by 45%. However, after five days exposure to this sub-ambient CO<sub>2</sub> concentration, the plants manifested an up-regulation of rubisco, which stimulated photosynthetic rates by 35%. Thus, plant acclimation responses can involve both an increase or decrease in specific enzymes, depending on the atmospheric CO<sub>2</sub> concentration.

In summary, many peer-reviewed studies suggest that as the CO<sub>2</sub> content of the air slowly but steadily rises, agricultural species may not necessarily exhibit photosynthetic acclimation, even under conditions of low soil nitrogen; for if a plant can maintain a balance between its sources and sinks for carbohydrates at the whole-plant level, acclimation should not be necessary. In addition, because earth's atmospheric CO<sub>2</sub> content is rising by an average of only 1.5 ppm per year, most plants should be able to either (1) adjust their relative growth rates by the small amount that would be needed to prevent low nitrogen-induced acclimation from ever occurring, or (2) expand their root systems by the small amount that would be needed to supply the extra nitrogen required to take full advantage of the CO<sub>2</sub>-induced increase in leaf carbohydrate production. However, in the event that a plant cannot initially balance its sources and sinks for carbohydrates at the whole-plant level, CO<sub>2</sub>-induced acclimation represents a beneficial secondary mechanism for achieving that balance through redistributing limiting resources away from the plant's photosynthetic machinery to strengthen sink development or enhance other nutrient-limiting processes.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/a/acclimationag.php>.

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#### 6.4.2. Chaparral and Desert Species

Roberts *et al.* (1998) conducted a FACE experiment in southern California, USA, exposing *Adenostoma fassiculatum* shrubs to atmospheric CO<sub>2</sub> concentrations of 360 and 550 ppm while they studied the nature of gas-exchange in this chaparral species. After six months of CO<sub>2</sub> fumigation, photosynthetic acclimation occurred. However, because of reductions in stomatal conductance and transpirational water loss, the CO<sub>2</sub>-enriched shrubs exhibited leaf water potentials that were less negative (and, hence, less stressful) than those of control plants. This CO<sub>2</sub>-induced water conservation phenomenon should enable this woody perennial to better withstand the periods of drought that commonly occur in this southern California region, while the photosynthetic down regulation it exhibits should allow it to more equitably distribute the limiting resources it possesses among different essential plant physiological processes.

Huxman and Smith (2001) measured seasonal gas exchange during an unusually wet El Niño year in an annual grass (*Bromus madritensis* ssp. *rubens*) and a perennial forb (*Eriogonum*

*inflatum*) growing within FACE plots established in the Mojave Desert, USA, which they maintained at atmospheric CO<sub>2</sub> concentrations of 350 and 550 ppm. The elevated CO<sub>2</sub> consistently increased net photosynthetic rates in the annual grass without inducing photosynthetic acclimation. In fact, even as seasonal photosynthetic rates declined post-flowering, the reduction was much less in the CO<sub>2</sub>-enriched plants. However, elevated CO<sub>2</sub> had no consistent effect on stomatal conductance in this species. In contrast, *Eriogonum* plants growing at 550 ppm CO<sub>2</sub> exhibited significant photosynthetic acclimation, especially late in the season, which led to similar rates of net photosynthesis in these plants in both CO<sub>2</sub> treatments. But in this species, elevated CO<sub>2</sub> *did* reduce stomatal conductance over most of the growing season. Hence, although both desert plants exhibited different stomatal and photosynthetic responses to elevated CO<sub>2</sub>, both experienced significant CO<sub>2</sub>-induced increases in water use efficiency and biomass production, thus highlighting the existence of different, but equally-effective, species-specific mechanisms for responding positively to atmospheric CO<sub>2</sub> enrichment in a desert environment.

In another study conducted at the Mojave Desert FACE site, Hamerlynck *et al.* (2002) determined that plants of the deciduous shrub *Lycium andersonii* grown in elevated CO<sub>2</sub> displayed photosynthetic acclimation, as maximum rubisco activity in the plants growing in the CO<sub>2</sub>-enriched air was 19% lower than in the plants growing in ambient air. Also, the elevated CO<sub>2</sub> did not significantly impact rates of photosynthesis. Leaf stomatal conductance, on the other hand, was consistently about 27% lower in the plants grown in the CO<sub>2</sub>-enriched air; and during the last month of the spring growing season, the plants in the elevated CO<sub>2</sub> plots displayed leaf water potentials that were less negative than those exhibited by the control plants growing in ambient air. Hence, as the CO<sub>2</sub> content of the air increases, *Lycium andersonii* will likely respond by exhibiting significantly enhanced water use efficiency, which should greatly increase its ability to cope with the highly variable precipitation and temperature regimes of the Mojave Desert. Moreover, the acclimation observed within the shrub's photosynthetic apparatus should allow it to reallocate more resources to producing and sustaining greater amounts of biomass. Thus, it is likely that future increases in the air's CO<sub>2</sub> content will favor a "greening" of the American Mojave Desert.

In summary, the few studies of the acclimation phenomenon that have been conducted on chaparral and desert plants indicate that although it can sometimes be complete, other physiological changes, such as the reductions in stomatal conductance that typically produce large increases in water use efficiency, often more than compensate for the sometimes small to negligible increases in photosynthesis.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/a/acclimationdesert.php>.

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### 6.4.3. Grassland Species

In nearly every reported case of photosynthetic acclimation in CO<sub>2</sub>-enriched plants, rates of photosynthesis displayed by grassland species *grown and measured at elevated CO<sub>2</sub> concentrations* are typically greater than those exhibited by control plants *grown and measured at ambient CO<sub>2</sub> concentrations* (Davey *et al.*, 1999; Bryant *et al.*, 1998).

As mentioned in prior sections, CO<sub>2</sub>-induced photosynthetic acclimation often results from insufficient plant sink strength, which can lead to carbohydrate accumulation in source leaves and the triggering of photosynthetic end-product feedback inhibition, which reduces rubisco activity and rates of net photosynthesis (Roumet *et al.*, 2000). As one example of this phenomenon, Rogers *et al.* (1998) reported that perennial ryegrass grown at an atmospheric CO<sub>2</sub> concentration of 600 ppm and *low* soil nitrogen exhibited leaf carbohydrate contents and rubisco activities that were 100% greater and 25% less, respectively, than those observed in control plants grown at 360 ppm CO<sub>2</sub>, prior to a cutting event. Following the cutting, which effectively reduced the source:sink ratio of the plants, leaf carbohydrate contents in CO<sub>2</sub>-enriched plants decreased and rubisco activities increased, completely ameliorating the photosynthetic acclimation in this species. However, at *high* soil nitrogen, photosynthetic acclimation to elevated CO<sub>2</sub> did *not* occur. Thus, photosynthetic acclimation appears to result from the inability of plants to develop adequate sinks at low soil nitrogen, and is not necessarily induced directly by atmospheric CO<sub>2</sub> enrichment.

In some cases, plants can effectively increase their sink strength and thus reduce the magnitude of CO<sub>2</sub>-induced acclimation by forming symbiotic relationships with certain species of soil fungi. Under such conditions, photosynthetic down regulation is not triggered as rapidly, or as frequently, by end-product feedback inhibition, as excess carbohydrates are mobilized out of source leaves and sent belowground to symbiotic fungi. Indeed, Staddon *et al.* (1999) reported that photosynthetic acclimation was not induced in CO<sub>2</sub>-enriched *Plantago lanceolata* plants that were inoculated with a mycorrhizal fungus, while it was induced in control plants that were not inoculated with the fungus. Thus, CO<sub>2</sub>-induced acclimation appears to be closely related to the source:sink balance that exists within plants, and is triggered when sink strength falls below, and source strength rises above, certain critical thresholds in a species-dependent manner.

As the CO<sub>2</sub> content of the air slowly but steadily rises, these peer-reviewed studies suggest that grassland species may not exhibit photosynthetic acclimation if they can maintain a balance



between their sources and sinks for carbohydrates at the whole-plant level. But in the event this balancing act is not initially possible, acclimation represents a beneficial secondary mechanism for ultimately achieving that balance by redistributing limiting resources away from the plant's photosynthetic machinery to strengthen its sink development and/or nutrient-gathering activities.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/a/acclimationgrass.php>.

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### 6.4.4. Tree Species

Trees grown for long periods of time in elevated CO<sub>2</sub> environments often, but not always (Marek *et al.*, 2001; Stylinski *et al.*, 2000; Bartak *et al.*, 1999; Schortemeyer *et al.*, 1999), exhibit some degree of photosynthetic acclimation or down regulation, which is typically characterized by modestly reduced rates of photosynthesis (compared to what might be expected on the basis of short-term exposure to CO<sub>2</sub>-enriched air) that result from a long-term decrease in the activity and/or amount of the primary plant carboxylating enzyme rubisco (Kubiske *et al.*, 2002; Egli *et al.*, 1998). This acclimation response in plants accustomed to growing in CO<sub>2</sub>-enriched air is characterized by short-term reductions in their rates of net photosynthesis when measured during short-term exposure to ambient air relative to net photosynthesis rates of comparable plants that have always been grown in ambient air.

Jach and Ceulemans (2000), for example, grew one-year-old Scots pine seedlings for two additional years at twice-ambient atmospheric CO<sub>2</sub> concentrations and reported that the elevated CO<sub>2</sub> increased the trees' mean rate of net photosynthesis by 64%. However, when measured during a brief return to ambient CO<sub>2</sub> concentrations, the normally-CO<sub>2</sub>-enriched seedlings exhibited an approximate 21% reduction in average net photosynthesis rate relative to that of seedlings that had always been exposed to ambient air. Similarly, Spunda *et al.* (1998) noted that a 350-ppm increase in the air's CO<sub>2</sub> concentration boosted rates of net photosynthesis in fifteen-year-old Norway spruce trees by 78%; but when net photosynthesis in the normally-CO<sub>2</sub>-enriched trees was measured at a temporary atmospheric CO<sub>2</sub> concentration of 350 ppm, an 18% reduction was observed relative to what was observed in comparable trees that had always been grown in ambient air. In fact, after reviewing the results of 15 different atmospheric CO<sub>2</sub> enrichment studies of European forest species growing in field environments maintained at twice-ambient CO<sub>2</sub> concentrations, Medlyn *et al.* (1999) found that the mean photosynthetic acclimation effect in the CO<sub>2</sub>-enriched trees was characterized by an average reduction of 19% in their rates of net photosynthesis when measured at temporary ambient CO<sub>2</sub> concentrations relative to the mean rate of net photosynthesis exhibited by those trees that had always been exposed to ambient air. Nonetheless, in nearly every reported case of CO<sub>2</sub>-induced photosynthetic acclimation in trees, the photosynthetic rates of trees *growing and measured in CO<sub>2</sub>-enriched air* have still been *much greater* than those exhibited by trees *growing and measured in ambient air*.

CO<sub>2</sub>-induced photosynthetic acclimation, when it occurs, often results from insufficient plant sink strength, which can lead to carbohydrate accumulation in source leaves and the triggering of photosynthetic end-product feedback inhibition, which results in reduced rates of net photosynthesis. Pan *et al.* (1998), for example, reported that apple seedlings grown at an atmospheric CO<sub>2</sub> concentration of 1600 ppm had foliar starch concentrations *17-fold greater* than those observed in leaves of seedlings grown at 360 ppm CO<sub>2</sub>, suggesting that this phenomenon likely triggered the reductions in leaf net photosynthesis rates they observed. Similarly, Rey and Jarvis (1998) reported that the accumulation of starch within leaves of CO<sub>2</sub>-enriched silver birch seedlings (100% above ambient) may have induced photosynthetic acclimation in that species. Also, in the study of Wiemken and Ineichen (2000), a 300-ppm increase in the air's CO<sub>2</sub> concentration induced seasonal acclimation in young spruce trees, where late-summer, fall and winter rates of net photosynthesis declined in conjunction with 40 to 50% increases in foliar glucose levels.

In some cases, trees can effectively increase their sink strength, and thus reduce the magnitude of CO<sub>2</sub>-induced photosynthetic acclimation, by forming symbiotic relationships with certain species of soil fungi. Under such conditions, photosynthetic down regulation is not triggered as rapidly, or as frequently, by end-product feedback inhibition, as excess carbohydrates are mobilized out of the trees' source leaves and sent belowground to support the growth of symbiotic fungi. Jifon *et al.* (2002), for example, reported that the degree of CO<sub>2</sub>-induced photosynthetic acclimation in sour orange tree seedlings was significantly reduced by the presence of mycorrhizal fungi, which served as sinks for excess carbohydrates synthesized by

the CO<sub>2</sub>-enriched seedlings. Thus, CO<sub>2</sub>-induced acclimation appears to be closely related to the source:sink balance that exists within plants; and it appears to be triggered when sink strength falls below, and source strength rises above, certain critical thresholds in a species-dependent manner.

During acclimation to elevated CO<sub>2</sub>, the amounts and activities of rubisco and/or other photosynthetic proteins are often reduced, which effectively increases the amount of nitrogen available for enhancing sink development or stimulating other nutrient-limited processes. As an example of this phenomenon, in the study of Blaschke *et al.* (2001), the authors reported that a doubling of the atmospheric CO<sub>2</sub> concentration reduced foliar rubisco concentrations by 15 and 30% in two mature oak species growing near CO<sub>2</sub>-emitting springs. Similarly, a 200-ppm increase in the air's CO<sub>2</sub> content reduced foliar rubisco concentrations in young aspen and birch seedlings by 39% (Takeuchi *et al.*, 2001) and 24% (Tjoelker *et al.*, 1998), respectively. Also, in two *Pinus radiata* studies, seedlings fumigated with air containing 650 ppm CO<sub>2</sub> displayed 30 to 40% reductions in rubisco concentration and rubisco activity relative to measurements made on seedlings grown in ambient air (Griffin *et al.*, 2000; Turnbull *et al.*, 1998). Other studies of CO<sub>2</sub>-enriched Norway spruce and Scots pines have documented CO<sub>2</sub>-induced reductions in foliar chlorophyll contents of 17% (Spunda *et al.*, 1998) and 26% (Gielen *et al.*, 2000), respectively. And in the study of Gleadow *et al.* (1998), elevated CO<sub>2</sub> led to acclimation in eucalyptus seedlings, which mobilized nitrogen away from rubisco and into prunasin, a sugar-based defense compound that deters herbivory.

In another interesting experiment, Polle *et al.* (2001) germinated acorns from oak trees exposed to ambient and CO<sub>2</sub>-enriched air and subsequently grew them at ambient and twice-ambient atmospheric CO<sub>2</sub> concentrations. They discovered that seedlings derived from acorns produced on CO<sub>2</sub>-enriched trees exhibited less-pronounced photosynthetic acclimation to elevated CO<sub>2</sub> than did seedlings derived from acorns produced on ambiently-grown trees, suggesting the possibility of generational adaptation to higher atmospheric CO<sub>2</sub> concentrations over even longer periods of time.

In summary, these many peer-reviewed scientific studies suggest that as the air's CO<sub>2</sub> content slowly but steadily rises, trees may be able to avoid photosynthetic acclimation if they maintain a proper balance between carbohydrate sources and sinks at the whole-tree level, which they may well be able to do in response to the current rate of rise of the air's CO<sub>2</sub> concentration (a mere 1.5 ppm per year). If a tree cannot *initially* balance its sources and sinks of carbohydrates, however, acclimation is an important and effective means of *ultimately* achieving that balance through redistributing essential resources away from the tree's photosynthetic machinery in an effort to strengthen sink development, enhance various nutrient-limited processes, and increase nutrient acquisition by, for example, stimulating the development of roots and their symbiotic fungal partners. And if those adjustments are not entirely successful, it is still the case that the acclimation process is hardly ever 100% complete (in the studies reviewed here it was on the order of 20%), so that tree growth is almost always significantly enhanced in CO<sub>2</sub>-enriched air in nearly every real-world setting.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/a/acclimationtree.php>.

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### **6.5. Competition**

Additional information on this topic, including reviews on competition not discussed here, can be found at [http://www.co2science.org/subject/c/subject\\_c.php](http://www.co2science.org/subject/c/subject_c.php) under the heading Competition.

#### **6.5.1. C<sub>3</sub> vs C<sub>4</sub> Plants**

C<sub>3</sub> plants typically respond better to atmospheric CO<sub>2</sub> enrichment than do C<sub>4</sub> plants in terms of increasing their rates of photosynthesis and biomass production. Hence, it has periodically been suggested that in a world of rising atmospheric CO<sub>2</sub> concentration, C<sub>3</sub> plants may out-compete C<sub>4</sub> plants and displace them, thereby decreasing the biodiversity of certain ecosystems. However, the story is much more complex than what is suggested by this simple scenario.

Wilson *et al.* (1998) grew 36 species of perennial grass common to tallgrass prairie ecosystems with and without arbuscular mycorrhizal fungi, finding that the dry matter production of the C<sub>3</sub> species that were colonized by the fungi was the same as that of the non-inoculated C<sub>3</sub> species, but that the fungal-colonized C<sub>4</sub> species produced, on average, 85% *more* dry matter than the non-inoculated C<sub>4</sub> species. This finding is of pertinence to the relative responsiveness of C<sub>3</sub> and C<sub>4</sub> plants to atmospheric CO<sub>2</sub> enrichment; for elevated levels of atmospheric CO<sub>2</sub> tend to enhance the mycorrhizal colonization of plant roots [see Fungi (Grasses and Herbaceous Plants)], which is known to make soil minerals and water more available for plant growth (see Nutrient Acquisition). Hence, this CO<sub>2</sub>-induced fungal-mediated growth advantage, which from this study appears to be more readily available to C<sub>4</sub> plants, could well counter the inherently greater biomass response of C<sub>3</sub> plants relative to that of C<sub>4</sub> plants, leveling the playing field relative to their competition for space in any given ecosystem.

Another advantage that may come to C<sub>4</sub> plants as a consequence of the ongoing rise in the air's CO<sub>2</sub> content was elucidated by BassiriRad *et al.* (1998), who found that elevated CO<sub>2</sub> enhanced the ability of the perennial C<sub>4</sub> grass *Bouteloua eriopoda* to increase its uptake of NO<sub>3</sub><sup>-</sup> and PO<sub>4</sub><sup>3-</sup> considerably more than the perennial C<sub>3</sub> shrubs *Larrea tridentata* and *Prosopis glandulosa*. Hence, it is not surprising that in an eight-year study of the effects of twice-ambient atmospheric CO<sub>2</sub> concentrations on a pristine tallgrass prairie in Kansas, Owensby *et al.* (1999) found that the elevated CO<sub>2</sub> did not affect the basal coverage of its C<sub>4</sub> species or their relative contribution to the composition of the ecosystem.

Then, of course, there is the well-known *antitranspirant effect* of atmospheric CO<sub>2</sub> enrichment (Pospisilova and Catsky, 1999), which is often more strongly expressed in C<sub>4</sub> plants than in C<sub>3</sub> plants and that typically allows C<sub>4</sub> plants to better cope with water stress. In a study of the C<sub>3</sub> dicot *Abutilon theophrasti* and the C<sub>4</sub> dicot *Amaranthus retroflexus*, for example, Ward *et al.*

(1999) found that *Amaranthus retroflexus* exhibited a greater relative recovery from drought than did the C<sub>3</sub> species, which suggests, in their words, that "the C<sub>4</sub> species would continue to be more competitive than the C<sub>3</sub> species in regions receiving more frequent and severe droughts," which basically characterizes regions where C<sub>4</sub> plants currently exist.

Two years later, Morgan *et al.* (2001) published the results of an open-top chamber study of a native shortgrass steppe ecosystem in Colorado, USA, where they had exposed the enclosed ecosystems to atmospheric CO<sub>2</sub> concentrations of 360 and 720 ppm for two six-month growing seasons. In spite of an average air temperature increase of 2.6°C, which was caused by the presence of the open-top chambers, the elevated CO<sub>2</sub> increased aboveground biomass production by an average of 38% in both years of the study; and when 50% of the standing green plant biomass was defoliated to simulate grazing halfway through the growing season, atmospheric CO<sub>2</sub> enrichment still increased aboveground biomass by 36%. It was also found that the communities enriched with CO<sub>2</sub> tended to have greater amounts of moisture in their soils than communities exposed to ambient air; and this phenomenon likely contributed to the less negative and, therefore, less stressful plant water potentials that were measured in the CO<sub>2</sub>-enriched plants. Last of all, the elevated CO<sub>2</sub> did not preferentially stimulate the growth of C<sub>3</sub> species over that of C<sub>4</sub> species in these communities. Hence, elevated CO<sub>2</sub> did not significantly affect the percentage composition of C<sub>3</sub> and C<sub>4</sub> species in these grasslands; and they maintained their original level of vegetative biodiversity.

In light of these several observations, we believe it to be highly unlikely that the ongoing rise in the air's CO<sub>2</sub> content will lead to C<sub>3</sub> plants replacing C<sub>4</sub> plants in the vast majority of earth's ecosystems. This would also appear to be the take-home message of the study of Wand *et al.* (1999), who in a massive review of the scientific literature published between 1980 and 1997 analyzed nearly 120 individual responses of C<sub>3</sub> and C<sub>4</sub> grasses to elevated CO<sub>2</sub>. On average, they found photosynthetic enhancements of 33 and 25%, respectively, for C<sub>3</sub> and C<sub>4</sub> plants, along with biomass enhancements of 44 and 33%, respectively, for a doubling of the air's CO<sub>2</sub> concentration. These larger-than-expected growth responses in the C<sub>4</sub> species led them to conclude that "it may be premature to predict that C<sub>4</sub> grass species will lose their competitive advantage over C<sub>3</sub> grass species in elevated CO<sub>2</sub>."

Further support for this conclusion comes from the study of Campbell *et al.* (2000), who reviewed research work done between 1994 and 1999 by a worldwide network of 83 scientists associated with the Global Change and Terrestrial Ecosystems (GCTE) Pastures and Rangelands Core Research Project 1, which resulted in the publication of over 165 peer-reviewed scientific journal articles. After analyzing this great body of research, they concluded that the "growth of C<sub>4</sub> species is about as responsive to CO<sub>2</sub> concentration as [is that of] C<sub>3</sub> species when water supply restricts growth, as is usual in grasslands containing C<sub>4</sub> species." Hence, the work of this group of scientists also provides no evidence for the suggestion that C<sub>3</sub> plants may out-compete C<sub>4</sub> plants and thereby replace them in a high-CO<sub>2</sub> world of the future.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/b/biodivc3vsc4.php>.

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### 6.5.2. N-Fixers vs. Non-N-Fixers

Will nitrogen-fixing (N-fixing) plants benefit more from atmospheric  $\text{CO}_2$  enrichment than non-N-fixers and thus obtain a competitive advantage over them that could lead to some non-N-fixers being excluded from certain plant communities, thereby decreasing the biodiversity of those ecosystems?

In a two-year glasshouse study of simulated low-fertility ecosystems composed of grassland species common to Switzerland, Stocklin and Korner (1999) found that atmospheric  $\text{CO}_2$  enrichment did indeed give nitrogen-fixing legumes an initial competitive advantage over non-N-fixers. However, it would be expected that, over time, a portion of the extra nitrogen fixed



by these legumes would become available to neighboring non-N-fixing species, which would then be able to use it to their own advantage, thereby preserving the species richness of the ecosystem over the long haul. Indeed, in a *four-year* study of an *established* (non-simulated) high grassland ecosystem located in the Swiss Alps, Arnone (1999) found that there was no difference between the minimal to non-existent growth responses of N-fixing and non-N-fixing species to elevated levels of atmospheric CO<sub>2</sub>. In addition, in a study of mixed plantings of the grass *Lolium perenne* and the legume *Medicago sativa*, Matthies and Egli (1999) found that elevated CO<sub>2</sub> did not influence the competition between the two plants, either directly or indirectly via its effects upon the root hemiparasite *Rhinanthus alectorolophus*; and in a study of mixed plantings of two grasses and two legumes, Navas *et al.* (1999) observed that plant responses to atmospheric CO<sub>2</sub> enrichment are more dependent upon neighboring plant *density* than they are upon neighboring plant *identity*.

In the few studies of this question that have been conducted to date, therefore, it would appear that there is little evidence to suggest that N-fixing legumes will out-compete non-N-fixing plants and eliminate them from any ecosystems.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/b/biodivnfixers.php>.

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### 6.5.3. Weeds vs. Non-Weeds

Elevated CO<sub>2</sub> typically stimulates the growth of nearly all plant species in monoculture, including those deemed undesirable by humans, i.e., weeds. Consequently, it is important to determine how future increases in the air's CO<sub>2</sub> content may influence relationships between weeds and non-weeds when they grow competitively in mixed-species stands.

Dukes (2002) grew model serpentine grasslands common to California, USA, in competition with the invasive forb *Centaurea solstitialis* at atmospheric CO<sub>2</sub> concentrations of 350 and 700 ppm for one year, determining that elevated CO<sub>2</sub> increased the biomass proportion of this weedy species in the community by a mere 1.2%, while total community biomass increased by 28%. Similarly, Gavazzi *et al.* (2000) grew loblolly pine seedlings for four months in competition with both C<sub>3</sub> and C<sub>4</sub> weeds at atmospheric CO<sub>2</sub> concentrations of 260 and 660 ppm, reporting that elevated CO<sub>2</sub> increased pine biomass by 22% while eliciting *no response at all* from either type of weed. Likewise, in a study of pasture ecosystems near Montreal, Canada, Taylor and Potvin (1997) found that elevated CO<sub>2</sub> concentrations did not influence the number of native species returning after their removal (to simulate disturbance), even in the face of the *introduced* presence of the C<sub>3</sub> weed *Chenopodium album*, which normally competes quite effectively with several slower-growing crops in ambient air. In fact, atmospheric CO<sub>2</sub> enrichment did not impact the growth of this weed in any measurable way.

Ziska *et al.* (1999) also studied the C<sub>3</sub> weed *C. album*, along with the C<sub>4</sub> weed *Amaranthus retroflexus*, in glasshouses maintained at atmospheric CO<sub>2</sub> concentrations of 360 and 720 ppm. They determined that elevated CO<sub>2</sub> significantly increased the photosynthetic rate and total dry weight of the C<sub>3</sub> weed, but that it had *no effect at all* on the C<sub>4</sub> weed. Also, they found that the growth response of the C<sub>3</sub> weed to a doubling of the air's CO<sub>2</sub> content was approximately 51%, which is about the same as the average 52% growth response tabulated by Idso (1992), and that obtained by Poorter (1993) for rapidly-growing wild C<sub>3</sub> species (54%), which finding suggests there is no enhanced dominance of the C<sub>3</sub> weed over other C<sub>3</sub> plants in a CO<sub>2</sub>-enriched environment.

Wayne *et al.* (1999) studied another agricultural weed, field mustard (*Brassica kaber*), which was sown in pots at six densities, placed in atmospheric CO<sub>2</sub> concentrations of 350 and 700 ppm, and sequentially harvested during the growing season. Early in stand development, elevated CO<sub>2</sub> increased aboveground weed biomass in a density-dependent manner; with the greatest stimulation of 141% occurring at the lowest density (corresponding to 20 plants per square meter) and the smallest stimulation of 59% occurring at the highest density (corresponding to 652 plants per square meter). However, as stands matured, the density-dependence of the CO<sub>2</sub>-induced growth response disappeared, and CO<sub>2</sub>-enriched plants exhibited an average aboveground biomass that was 34% greater than that of ambiently-grown plants across a broad range of plant densities. Moreover, this final growth stimulation was similar to that of most other herbaceous plants exposed to atmospheric CO<sub>2</sub> enrichment (30 to 50% biomass increases for a doubling of the air's CO<sub>2</sub> content), once again evidencing that atmospheric CO<sub>2</sub> enrichment confers no undue advantage upon weeds at the expense of other plants.

In a study of a weed that affects both plants and animals, Caporn *et al.* (1999) examined bracken (*Pteridium aquilinum*), which poses a serious weed problem and potential threat to human health in the United Kingdom and other regions, growing specimens for 19 months in controlled environment chambers maintained at atmospheric CO<sub>2</sub> concentrations of 370 and 570 ppm and normal or high levels of soil fertility. They found that the high CO<sub>2</sub> treatment

consistently increased rates of net photosynthesis by 30 to 70%, depending on soil fertility and time of year. However, elevated CO<sub>2</sub> did *not* increase total plant dry mass or the dry mass of any plant organ, including rhizomes, roots and fronds. In fact, the only significant effect of elevated CO<sub>2</sub> on bracken growth was observed in the normal nutrient regime, where elevated CO<sub>2</sub> actually *reduced* mean frond area.

Finally, in a study involving two parasitic species (*Striga hermonthica* and *Striga asiatica*), Watling and Press (1997) reported that total parasitic biomass per host plant at an atmospheric CO<sub>2</sub> concentration of 700 ppm was 65% less than it was in ambient air. And in a related study, Dale and Press (1999) observed that the presence of a parasitic plant (*Orobanche minor*) reduced its host's biomass by 47% in ambient air of 360 ppm CO<sub>2</sub>, while it only reduced it by 20% in air of 550 ppm CO<sub>2</sub>.

These several studies suggest that, contrary to what is claimed by the alarmists, the ongoing rise in the air's CO<sub>2</sub> content likely will *not* favor the growth of weedy species over that of crops and native plants. In fact, it may well provide non-weeds greater protection against weed-induced decreases in their productivity and growth. Thus, future increases in the air's CO<sub>2</sub> content may actually increase the competitiveness of non-weeds over weeds.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/b/weedsvsnw.php>.

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## **6.6. Respiration**

Nearly all of earth's plants respond favorably to increases in the air's CO<sub>2</sub> concentration by exhibiting enhanced rates of net photosynthesis and biomass production. In many cases, observed increases in these parameters (especially biomass production) are believed to be due, in part, to CO<sub>2</sub>-induced reductions in carbon losses via respiration, which seems only logical (albeit appearances may sometimes be deceiving), for with less carbon being respired under CO<sub>2</sub>-enriched conditions, rates of net carbon assimilation and its incorporation into plant organic matter would be expected to rise, as they indeed do in most cases when the air's CO<sub>2</sub> content is increased. In this section, therefore, we examine what has been learned about this subject from experiments conducted on various herbaceous and woody plants.

Additional information on this topic, including reviews on respiration not discussed here, can be found at [http://www.co2science.org/subject/r/subject\\_r.php](http://www.co2science.org/subject/r/subject_r.php) under the heading Respiration.

### **6.6.1. Herbaceous Plants**

#### **6.6.1.1. Crops**

Baker *et al.* (2000) grew rice in Soil-Plant-Atmosphere Research (SPAR) units at atmospheric CO<sub>2</sub> concentrations of 350 and 700 ppm during daylight hours. Under these conditions, rates of dark respiration decreased in both CO<sub>2</sub> treatments with short-term increases in the air's CO<sub>2</sub> concentration at night. However, when dark respiration rates were measured at the CO<sub>2</sub> growth concentrations of the plants, they were *not* significantly different from each other.

Cousins *et al.* (2001) grew sorghum at atmospheric CO<sub>2</sub> concentrations of 370 and 570 ppm within a Free-Air CO<sub>2</sub>-Enrichment (FACE) facility near Phoenix, Arizona, USA. Within six days of planting, the photosynthetic rates of the second leaves of the CO<sub>2</sub>-enriched plants were 37% greater than those of the second leaves of the ambiently-grown plants. However, this CO<sub>2</sub>-induced photosynthetic enhancement slowly declined with time, stabilizing at approximately 15% between 23 and 60 days after planting. In addition, when measuring photosynthetic rates at a reduced oxygen concentration of 2%, they observed 16 and 9% increases in photosynthesis for the ambient and CO<sub>2</sub>-enriched plants, respectively. These observations suggest that the extra 200 ppm of CO<sub>2</sub> was reducing photorespiratory carbon losses, although this phenomenon did not account for all of the CO<sub>2</sub>-induced stimulation of photosynthesis.

Das *et al.* (2002) grew tropical nitrogen-fixing mungbean plants in open-top chambers maintained at atmospheric CO<sub>2</sub> concentrations of either 350 or 600 ppm for two growing

seasons, with the extra CO<sub>2</sub> being provided between either days 0 and 20 or days 21 and 40 after germination. This work revealed that the elevated CO<sub>2</sub> decreased rates of respiration by 54-62%, with the greatest declines occurring during the first 20 days after germination.

Wang *et al.* (2004) grew well-watered and fertilized South American tobacco plants from seed in 8.4-liter pots (one plant per pot) filled with sand and housed in controlled-environment growth chambers maintained at atmospheric CO<sub>2</sub> concentrations of either 365 or 730 ppm for a total of nine weeks. Over this period they found that the ratio of net photosynthesis per unit leaf area (A) to dark respiration per unit leaf area (Rd) "changed dramatically." Whereas A/Rd was the same in both treatments at the beginning of the measurement period, a month later it had doubled in the CO<sub>2</sub>-enriched environment but had risen by only 58% in the ambient treatment. Speaking of this finding, the three researchers say that "if the dynamic relationship between A and Rd observed in *N. sylvestris* is applicable to other species, it will have important implications for carbon cycling in terrestrial ecosystems, since plants will assimilate CO<sub>2</sub> more efficiently as they mature."

Bunce (2005) grew soybeans in the field in open-top chambers maintained at atmospheric CO<sub>2</sub> concentrations of ambient and ambient +350 ppm at the Beltsville Agricultural Research Center in Maryland (USA), where net carbon dioxide exchange rate measurements were performed on a total of 16 days between 18 July and 11 September of 2000 and 2003, during the flowering to early pod-filling stages of the growing season. Averaged over the course of the study, he found that daytime net photosynthesis per unit leaf area was 48% greater in the plants growing in the CO<sub>2</sub>-enriched air, while nighttime respiration per unit leaf area was unaffected by elevated CO<sub>2</sub>. However, because the extra 350 ppm of CO<sub>2</sub> increased leaf dry mass per unit area by an average of 23%, respiration per unit of mass was significantly lower for the leaves of the soybeans growing in the CO<sub>2</sub>-enriched air.

Wang and Curtis (2002) conducted a meta-analysis of the results of 45 area-based dark respiration (Rda) and 44 mass-based dark respiration (Rdm) assessments of the effects of a doubling of the air's CO<sub>2</sub> concentration on 33 species of plants derived from 37 scientific studies. This work revealed that the mean leaf Rda of the suite of herbaceous plants studied was significantly *higher* (+29%,  $P < 0.01$ ) at elevated CO<sub>2</sub> than at ambient CO<sub>2</sub>. However, when the herbaceous plants were separated into groups that had experienced durations of CO<sub>2</sub> enrichment that were either shorter or longer than 60 days, it was found that the short-term studies exhibited a mean Rda increase of 51% ( $P < 0.05$ ), while the long-term studies exhibited *no effect*. Hence, for conditions of *continuous* atmospheric CO<sub>2</sub> enrichment, herbaceous plants would likely experience no change in leaf Rda. In addition, the two researchers found that plants exposed to elevated CO<sub>2</sub> for < 100 days "showed significantly less of a reduction in leaf Rdm due to CO<sub>2</sub> enrichment (-12%) than did plants exposed for longer periods (-35%,  $P < 0.01$ )." Hence, for long-term conditions of *continuous* atmospheric CO<sub>2</sub> enrichment, herbaceous crops would likely experience an approximate 35% decrease in leaf Rdm.

Bunce (2004) grew six different 16-plant batches of soybeans within a single controlled-environment chamber, one to a pot filled with 1.8 liters of vermiculite that was flushed daily

with a complete nutrient solution. In three experiments conducted at day/night atmospheric CO<sub>2</sub> concentrations of 370/390 ppm, air temperatures were either 20, 25 or 30°C, while in three other experiments conducted at an air temperature of 25°C, atmospheric CO<sub>2</sub> concentrations were either 40, 370 or 1400 ppm. At the end of the normal 16 hours of light on the 17th day after planting, half of the plants were harvested and used for the measurement of a number of physical parameters, while measurements of the plant physiological processes of respiration, translocation and nitrate reduction were made on the other half of the plants over the following 8-hour dark period.

Plotting translocation and nitrate reduction as functions of respiration, Bunce found that "a given change in the rate of respiration was accompanied by the same change in the rate of translocation or nitrate reduction, regardless of whether the altered respiration was caused by a change in temperature or by a change in atmospheric CO<sub>2</sub> concentration." As a result, and irrespective of whatever mechanisms may have been involved in eliciting the responses observed, Bunce logically concluded that "the parallel responses of translocation and nitrate reduction for both the temperature and CO<sub>2</sub> treatments make it unlikely that the response of respiration to one variable [CO<sub>2</sub>] was an artifact while the response to the other [temperature] was real." Hence, there is reason to believe that the oft-observed decreases in dark respiration experienced by plants exposed to elevated levels of atmospheric CO<sub>2</sub>, as per the review and analysis studies of Drake *et al.* (1999) and Wang and Curtis (2002), are indeed real and not the result of measurement system defects.

In light of these several findings, it can probably be validly concluded that the balance of evidence suggests that the growth of herbaceous crops is generally not only enhanced by CO<sub>2</sub>-induced increases in net photosynthesis during the light period of the day, it is also enhanced by CO<sub>2</sub>-induced decreases in respiration during the dark period.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/r/respirationcrops.php>.

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Wang, X. and Curtis, P. 2002. A meta-analytical test of elevated CO<sub>2</sub> effects on plant respiration. *Plant Ecology* **161**: 251-261.

#### 6.6.1.2. Other

In this section we review the results of a smattering of studies of non-crop herbaceous plants in an attempt to determine if atmospheric CO<sub>2</sub> enrichment tends to increase or decrease (or leave unaltered) their respiration rates.

Rabha and Uprety (1998) grew India mustard plants for an entire season in open-top chambers with either ambient or enriched (600 ppm) atmospheric CO<sub>2</sub> concentrations and adequate or inadequate soil moisture levels. Their work revealed that the elevated CO<sub>2</sub> concentration reduced leaf dark respiration rates by about 25% in both soil moisture treatments, which suggests that a greater proportion of the increased carbohydrate pool in the CO<sub>2</sub>-enriched plants remained within them to facilitate increases in growth and development.

Ziska and Bunce (1999) grew four C<sub>4</sub> plants in controlled environment chambers maintained at either full-day (24-hour) atmospheric CO<sub>2</sub> concentrations of 350 and 700 ppm or a nocturnal-only CO<sub>2</sub> concentration of 700 ppm (with 350 ppm CO<sub>2</sub> during the day) for about three weeks. In this particular study, 24-hour CO<sub>2</sub> enrichment caused a significant increase in the photosynthesis (+13%) and total dry mass (+21%) of only one of the four C<sub>4</sub> species (*Amaranthus retroflexus*). However, there was *no significant effect* of nocturnal-only CO<sub>2</sub> enrichment on this species, indicating that the observed increase in biomass, resulting from 24-hour atmospheric CO<sub>2</sub> enrichment, was *not* facilitated by greater carbon conservation stemming from a CO<sub>2</sub>-induced reduction in dark respiration.

In an experiment that produced essentially the same result, Grunzweig and Korner (2001) constructed model grasslands representative of the Negev of Israel and placed them in growth chambers maintained at atmospheric CO<sub>2</sub> concentrations of 280, 440 and 600 ppm for five months. This study also revealed that atmospheric CO<sub>2</sub> enrichment had *no effect* on nighttime respiratory carbon losses.

Moving to the other end of the moisture spectrum, Van der Heijden *et al.* (2000) grew peat moss hydroponically within controlled environment chambers maintained at atmospheric CO<sub>2</sub> concentrations of 350 and 700 ppm for up to six months, while simultaneously subjecting the peat moss to three different levels of nitrogen deposition. In all cases, they found that the elevated CO<sub>2</sub> reduced rates of dark respiration consistently throughout the study by 40 to 60%. In a final multi-species study, Gonzalez-Meler *et al.* (2004) reviewed the scientific literature pertaining to the effects of atmospheric CO<sub>2</sub> enrichment on plant respiration from the cellular level to the level of entire ecosystems. They report finding that "contrary to what was previously thought, specific respiration rates are generally not reduced when plants are grown at elevated CO<sub>2</sub>." Nevertheless, they note that "whole ecosystem studies show that canopy respiration does not increase proportionally to increases in biomass in response to elevated CO<sub>2</sub>," which suggests that *respiration per unit biomass* is likely somewhat *reduced* by atmospheric CO<sub>2</sub> enrichment. However, they also find that "a larger proportion of respiration takes place in the root system [when plants are grown in CO<sub>2</sub>-enriched air]," which once again obfuscates the issue.

The three researchers ultimately conclude that "fundamental information is still lacking on how respiration and the processes supported by it are physiologically controlled, thereby preventing sound interpretations of what seem to be species-specific responses of respiration to elevated CO<sub>2</sub>." Hence, they refreshingly state that "the role of plant respiration in augmenting the sink capacity of terrestrial ecosystems is still uncertain," setting an example of wise restraint that many climate alarmists and politicians would do well to follow with respect to questions about many other aspects of CO<sub>2</sub> effects (and non-effects!) on climate and biology.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/r/respirationherbaceous.php>.

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## 6.6.2. Woody Plants

### 6.6.2.1. Coniferous Trees

Jach and Ceulemans (2000) grew three-year old Scots pine seedlings out-of-doors and rooted in the ground in open-top chambers maintained at atmospheric CO<sub>2</sub> concentrations of either 350 or 750 ppm for two years; and to make the experiment even more representative of the natural world, they applied no nutrients or irrigation water to the soils in which the trees grew for the duration of the study. After two years of growth under these conditions, dark respiration on a needle mass basis in the CO<sub>2</sub>-enriched seedlings was 27% and 33% lower in current-year and one-year-old needles, respectively, with the greater reduction in the older needles being thought to arise from the greater duration of elevated CO<sub>2</sub> exposure experienced by those needles.

Hamilton *et al.* (2001) studied the short- and long-term respiratory responses of loblolly pines in a free-air CO<sub>2</sub>-enrichment (FACE) study that was established in 1996 on 13-year-old trees in a North Carolina (USA) plantation, where the CO<sub>2</sub>-enriched trees were exposed to an extra 200 ppm of CO<sub>2</sub>. This modest increase in the atmosphere's CO<sub>2</sub> concentration produced no significant short-term suppression of *dark* respiration rates in the trees' needles. Neither did long-term exposure to elevated CO<sub>2</sub> alter *maintenance* respiration, which is the amount of CO<sub>2</sub> respired to maintain existing plant tissues. However, *growth* respiration, which is the amount of CO<sub>2</sub> respired when constructing new tissues, was reduced by 21%.

McDowell *et al.* (1999) grew five-month-old seedlings of western hemlock in root boxes subjected to various root-space CO<sub>2</sub> concentrations (ranging from 90 to 7000 ppm) for periods of several hours to determine the effects of soil CO<sub>2</sub> concentration on growth, maintenance and total root respiration. In doing so, they found that although elevated CO<sub>2</sub> had no effect on growth respiration, it significantly impacted maintenance and total respiration. At a soil CO<sub>2</sub> concentration of 1585 ppm, for example, total and maintenance respiration rates of roots were 55% and 60% lower, respectively, than they were at 395 ppm. In fact, the impact of elevated CO<sub>2</sub> on maintenance respiration was so strong that it exhibited an exponential decline of about 37% for every doubling of soil CO<sub>2</sub> concentration. The implications of this observation are especially important, since maintenance respiration comprised 85% of total root respiration in this study.

The results of these experiments suggest that both above and below the soil surface, coniferous trees *might* exhibit reductions in total respiration in a high-CO<sub>2</sub> world of the future. Three studies of but three species, however, is no guarantee of anything. Hence, it is important to consider the findings described in this summary within the broader context provided by the results of experiments conducted on other woody plants, as well as herbaceous plants, as summarized here.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/r/respirationconifers.php>.

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Hamilton, J.G., Thomas, R.B. and DeLucia, E.H. 2001. Direct and indirect effects of elevated CO<sub>2</sub> on leaf respiration in a forest ecosystem. *Plant, Cell and Environment* **24**: 975-982.

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### 6.6.2.2. Deciduous Trees

Wang and Curtis (2001) grew cuttings of two male and two female trembling aspen trees for about five months on soils containing low and high nitrogen contents in open-top chambers maintained at atmospheric CO<sub>2</sub> concentrations of 380 and 765 ppm, finding that gender had little effect on dark respiration rates, but that elevated CO<sub>2</sub> *increased* them, by 6% and 32% in the low and high soil nitrogen treatments, respectively. On the other hand, Karnosky *et al.* (1999) grew both O<sub>3</sub>-sensitive and O<sub>3</sub>-tolerant aspen clones for one full year in free-air CO<sub>2</sub>-enrichment (FACE) plots maintained at atmospheric CO<sub>2</sub> concentrations of 360 and 560 ppm, finding that the extra CO<sub>2</sub> *decreased* dark respiration rates by 24%.

Gielen *et al.* (2003) measured stem respiration rates of white, black and robusta poplar trees in a high-density forest plantation in the third year of a FACE experiment in which the CO<sub>2</sub> concentration of the air surrounding the trees was increased to a value of approximately 550 ppm. This study revealed, in their words, that "stem respiration rates were not affected by the FACE treatment," and that "FACE did not influence the relationships between respiration rate and both stem temperature and relative growth rate." In addition, they say they could find "no effect of the FACE treatment on R<sub>m</sub> [maintenance respiration, which is related to the sustaining of existing cells] and R<sub>g</sub> [growth respiration, which is related to the synthesis of new tissues]."

Hamilton *et al.* (2001) studied respiratory responses of sweetgum trees growing in the understory of a loblolly pine plantation (but occasionally reaching the top of the canopy) to an extra 200 ppm of CO<sub>2</sub> in a FACE study conducted in North Carolina, USA. As a result of their measurement program, they determined that the modest increase in atmospheric CO<sub>2</sub>

concentration did not appear to alter maintenance respiration to any significant degree, but that it reduced dark respiration by an average of 10% and growth respiration of leaves at the top of the canopy by nearly 40%.

In reviewing the results of these several deciduous tree studies, we see cases of both *increases* and *decreases* in respiration rates in response to atmospheric CO<sub>2</sub> enrichment, as well as cases of *no change* in respiration. Hence, as we concluded to be the situation with conifers, more data are needed before any general conclusions may safely be drawn about the effects of atmospheric CO<sub>2</sub> enrichment on the respiration rates of deciduous trees.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/r/respirationdeciduous.php>.

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Hamilton, J.G., Thomas, R.B. and DeLucia, E.H. 2001. Direct and indirect effects of elevated CO<sub>2</sub> on leaf respiration in a forest ecosystem. *Plant, Cell and Environment* **24**: 975-982.

Karnosky, D.F., Mankovska, B., Percy, K., Dickson, R.E., Podila, G.K., Sober, J., Noormets, A., Hendrey, G., Coleman, M.D., Kubiske, M., Pregitzer, K.S. and Isebrands, J.G. 1999. Effects of tropospheric O<sub>3</sub> on trembling aspen and interaction with CO<sub>2</sub>: results from an O<sub>3</sub>-gradient and a FACE experiment. *Water, Air, and Soil Pollution* **116**: 311-322.

Wang, X. and Curtis, P.S. 2001. Gender-specific responses of *Populus tremuloides* to atmospheric CO<sub>2</sub> enrichment. *New Phytologist* **150**: 675-684.

#### 6.6.2.3. Multiple Tree Studies

Amthor (2000) measured dark respiration rates of intact leaves of nine different tree species growing naturally in an American deciduous forest. Within a specially designed leaf chamber, the CO<sub>2</sub> concentration surrounding individual leaves was stabilized at 400 ppm for 15 minutes, whereupon their respiration rates were measured for 30 minutes, after which the CO<sub>2</sub> concentration in the leaf chamber was raised to 800 ppm for 15 minutes and respiration data were again recorded for the same leaves. This protocol revealed that elevated CO<sub>2</sub> had little effect on leaf dark respiration rates. In fact, the extra 400 ppm of CO<sub>2</sub> within the measurement cuvette decreased the median respiration rate by only 1.5% across the nine tree species. This observation thus led Amthor to state that the "rising atmospheric CO<sub>2</sub> concentration has only a small direct effect on tree leaf respiration in deciduous forests;" and he calculated that it can be "more than eliminated by a 0.22°C temperature increase." Upon this premise, he thus concluded that "future direct effects of increasing CO<sub>2</sub> in combination with warming could stimulate tree leaf respiration in their sum," and that this consequence "would translate into only slight, if any, effects on the carbon balance of temperate deciduous forests in a future atmosphere containing as much as [800 ppm] CO<sub>2</sub>."

Amthor's conclusion, however, is debatable, for it is based upon the extrapolation of the short-term respiratory responses of *individual leaves*, exposed to elevated CO<sub>2</sub> *for only an hour or two*, to that of *entire trees*, many of which will experience rising CO<sub>2</sub> levels *for over a century or more* during their lifetimes. Trees are long-lived organisms that should not be expected to reveal the ultimate nature of their long-term responses to elevated atmospheric CO<sub>2</sub> concentrations on as short a time scale as that employed by Amthor. Indeed, their initial respiratory responses may change significantly with the passage of time, as they acclimate and optimize their physiology and growth patterns to the gradually-rising CO<sub>2</sub> content of earth's atmosphere, as evidenced by the findings of the following two studies.

Wang and Curtis (2002) conducted a meta-analysis of the results of 45 *area*-based dark respiration (Rda) and 44 *mass*-based dark respiration (Rdm) assessments of the effects of an approximate doubling of the air's CO<sub>2</sub> concentration on 33 species of plants (both herbaceous and woody) derived from 37 scientific publications. This effort revealed that the mean leaf Rda of the woody plants they analyzed was unaffected by elevated CO<sub>2</sub>. However, there *was* an effect on mean leaf Rdm, and it was determined to be *time-dependent*. The woody plants exposed to elevated CO<sub>2</sub> for < 100 days, in the reviewing scientists' words, "showed significantly less of a reduction in leaf Rdm due to CO<sub>2</sub> enrichment (-12%) than did plants exposed for longer periods (-35%, P < 0.01)." Hence, *for conditions of continuous long-term atmospheric CO<sub>2</sub> enrichment*, the results of Wang and Curtis' analysis suggest that woody plants may well experience an approximate 35% *decrease* in leaf Rdm.

Drake *et al.* (1999) also conducted a comprehensive analysis of the peer-reviewed scientific literature to determine the effects of elevated atmospheric CO<sub>2</sub> concentrations on plant respiration rates. In doing so, they found that atmospheric CO<sub>2</sub> enrichment typically decreased respiration rates in mature foliage, stems, and roots of CO<sub>2</sub>-enriched plants relative to rates measured in plants grown in ambient air; and when normalized on a biomass basis, they determined that a doubling of the atmosphere's CO<sub>2</sub> concentration would likely reduce plant respiration rates by an average of 18%. To determine the potential effects of this phenomenon on annual global carbon cycling, which the twelve researchers say "will enhance the quantity of carbon stored by forests," they input a 15% CO<sub>2</sub>-induced respiration reduction into a carbon sequestration model, finding that an additional 6 to 7 Gt of carbon would remain sequestered within the terrestrial biosphere each year, thus substantially strengthening the terrestrial carbon sink.

More recently, however, Davey *et al.* (2004) have reversed our view of the subject yet again. "Averaged across many previous investigations," as they put it, "doubling the CO<sub>2</sub> concentration has frequently been reported to cause an instantaneous reduction of leaf dark respiration measured as CO<sub>2</sub> efflux." However, as they continue, "no known mechanism accounts for this effect, and four recent studies [Amthor (2000); Amthor *et al.* (2001); Jahnke (2001); Jahnke and Krewitt (2002)] have shown that the measurement of respiratory CO<sub>2</sub> efflux is prone to experimental artifacts that could account for the reported response."

Using a technique that avoids the potential artifacts of prior attempts to resolve the issue, Davey *et al.* employed a high-resolution dual channel oxygen analyzer in an open gas exchange system to measure the respiratory O<sub>2</sub> uptake of nine different species of plants in response to a short-term increase in atmospheric CO<sub>2</sub> concentration, as well as the response of seven species to long-term elevation of the air's CO<sub>2</sub> content in four different field experiments. In doing so, they found that "over six hundred separate measurements of respiration failed to reveal any decrease in respiratory O<sub>2</sub> uptake with an instantaneous increase in CO<sub>2</sub>." Neither could they detect any response to a five-fold increase in the air's CO<sub>2</sub> concentration nor to the total removal of CO<sub>2</sub> from the air. They also note that "this lack of response of respiration to elevated CO<sub>2</sub> was independent of treatment method, developmental stage, beginning or end of night, and the CO<sub>2</sub> concentration at which the plants had been grown." In the long-term field studies, however, there *was* a respiratory response; but it was *small* (7% on a leaf mass basis), and it was *positive*, not negative.

So what is one to ultimately conclude about the matter? Perhaps the most reasonable conclusion would be that atmospheric CO<sub>2</sub> enrichment may either increase or decrease woody-plant respiration, but not to any great degree, and that *in the mean*, the net result for the conglomerate of earth's trees would likely be something of little impact, one way or the other.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/r/respirationtrees.php>.

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Drake, B.G., Azcon-Bieto, J., Berry, J., Bunce, J., Dijkstra, P., Farrar, J., Gifford, R.M., Gonzalez-Meler, M.A., Koch, G., Lambers, H., Siedow, J. and Wullschlegel, S. 1999. Does elevated atmospheric CO<sub>2</sub> inhibit mitochondrial respiration in green plants? *Plant, Cell and Environment* **22**: 649-657.

Jahnke, S. 2001. Atmospheric CO<sub>2</sub> concentration does not directly affect leaf respiration in bean or poplar. *Plant, Cell and Environment* **24**: 1139-1151.

Jahnke, S. and Krewitt, M. 2002. Atmospheric CO<sub>2</sub> concentration may directly affect leaf respiration measurement in tobacco, but not respiration itself. *Plant, Cell and Environment* **25**: 641-651.

Wang, X. and Curtis, P. 2002. A meta-analytical test of elevated CO<sub>2</sub> effects on plant respiration. *Plant Ecology* **161**: 251-261.

## **6.7. Other Benefits**

### **6.7.1. Isoprene**

Isoprene (C<sub>5</sub>H<sub>8</sub> or 2-methyl-1,3-butadiene) is a highly reactive *non-methane hydrocarbon* (NMHC) that is emitted in copious quantities by vegetation and is responsible for the production of vast amounts of tropospheric ozone (Chameides *et al.*, 1988; Harley *et al.*, 1999), which is a debilitating scourge of plant and animal life alike. In fact, it has been calculated by Poisson *et al.* (2000) that current levels of NMHC emissions -- the vast majority of which are isoprene, accounting for more than twice as much as all other NMHCs combined -- may increase surface ozone concentrations by up to 40% in the marine boundary-layer and 50-60% over land, and that the current tropospheric ozone content extends the atmospheric lifetime of methane -- one of the world's most powerful greenhouse gases -- by approximately 14%. Consequently, it can be appreciated that anything that reduces isoprene emissions from vegetation is something to be desired; and in this section we briefly review what has been learned in this regard about the ongoing rise in the atmosphere's CO<sub>2</sub> concentration.

Although a few experiments conducted on certain plant species have suggested that elevated concentrations of atmospheric CO<sub>2</sub> have little to no effect on their emissions of isoprene (Buckley, 2001; Baraldi *et al.*, 2004; Rapparini *et al.*, 2004), a much larger number of other experiments are suggestive of substantial CO<sub>2</sub>-induced *reductions* in isoprene emissions, as demonstrated by the work of Monson and Fall (1989), Loreto and Sharkey (1990), Sharkey *et al.* (1991) and Loreto *et al.* (2001). Short synopses of several *other* such studies are therefore briefly described in the following paragraphs, along with some of the implications of their more robust findings.

Rosentiel *et al.* (2003) studied three 50-tree cottonwood plantations growing in separate mesocosms within the forestry section of the Biosphere 2 facility near Oracle, Arizona, USA, one of which mesocosms was maintained at an atmospheric CO<sub>2</sub> concentration of 430 ppm, while the other two were enriched to concentrations of 800 and 1200 ppm for one entire growing season. Integrated over that period, the total above-ground biomass of the trees in the latter two mesocosms was *increased* by 60% and 82%, respectively, while their production of isoprene was *decreased* by 21% and 41%, respectively.

Scholefield *et al.* (2004) measured isoprene emissions from *Phragmites australis* plants (one of the world's most important natural grasses) growing at different distances from a natural CO<sub>2</sub> spring in central Italy. At the specific locations they chose to make their measurements, atmospheric CO<sub>2</sub> concentrations of approximately 350, 400, 550 and 800 ppm had likely prevailed for the entire lifetimes of the plants. Across this CO<sub>2</sub> gradient, plant isoprene emissions dropped ever lower as the air's CO<sub>2</sub> concentration rose ever higher. Over the first 50-

ppm CO<sub>2</sub> increase, isoprene emissions were reduced to approximately 65% of what they were at ambient CO<sub>2</sub>, while for CO<sub>2</sub> increases of 200 and 450 ppm, they were reduced to only about 30% and 7% of what they were in the 350-ppm-CO<sub>2</sub> air. The researchers note that these reductions were likely caused by reductions in leaf isoprene synthase, which was observed to be highly correlated with isoprene emissions, leading them to conclude that "elevated CO<sub>2</sub> generally inhibits the expression of isoprenoid synthesis genes and isoprene synthase activity which may, in turn, limit formation of every chloroplast-derived isoprenoid." Hence, they state that the "basal emission rate of isoprene is likely to be reduced under future elevated CO<sub>2</sub> levels."

Centritto *et al.* (2004) grew hybrid poplar saplings for one full growing season in a FACE facility located at Rapolano, Italy, where the air's CO<sub>2</sub> concentration was increased by approximately 200 ppm. Their study demonstrated, in their words, that "isoprene emission is reduced in elevated CO<sub>2</sub>, in terms of both maximum values of isoprene emission rate and isoprene emission per unit of leaf area averaged across the total number of leaves per plant," which in their case amounted to a reduction of approximately 34%. When isoprene emission was summed over the entire plant profile, however, the reduction was not nearly so great (only 6%), because of the greater number of leaves on the CO<sub>2</sub>-enriched saplings. "However," as they state, "Centritto *et al.* (1999), in a study with potted cherry seedlings grown in open-top chambers, and Gielen *et al.* (2001), in a study with poplar saplings exposed to FACE, showed that the stimulation of total leaf area in response to elevated CO<sub>2</sub> was a transient effect, because it occurred only during the first year of growth." Hence, they concluded "it may be expected that with similar levels of leaf area, the integrated emission of isoprene would have been much lower in elevated CO<sub>2</sub>." Indeed, they say that their data, "as well as that reported by Scholefield *et al.* (2004), in a companion experiment on *Phragmites* growing in a nearby CO<sub>2</sub> spring, mostly confirm that isoprene emission is inversely dependent on CO<sub>2</sub> [concentration] when this is above ambient, and suggests that a lower fraction of C will be re-emitted in the atmosphere as isoprene by single leaves in the future."

Working at another FACE facility, the Aspen FACE facility near Rhinelander, Wisconsin, USA, Calfapietra *et al.* (2008) measured emissions of isoprene from sun-exposed upper-canopy leaves of an O<sub>3</sub>-tolerant clone and an O<sub>3</sub>-sensitive clone of trembling aspen (*Populus tremuloides* Michx.) trees that were growing in either normal ambient air, air enriched with an extra 190-200 ppm CO<sub>2</sub>, air with 1.5 times the normal ozone concentration, or air simultaneously enriched with the identical concentrations of both of these atmospheric trace gases. Results of their analysis showed that for the trees growing in air of ambient ozone concentration, the extra 190 ppm of CO<sub>2</sub> *decreased* the mean isoprene emission rate by 11.7% in the O<sub>3</sub>-tolerant aspen clone and by 22.7% in the O<sub>3</sub>-sensitive clone, while for the trees growing in air with 1.5 times the ambient ozone concentration, the extra CO<sub>2</sub> also *decreased* the mean isoprene emission rate by 10.4% in the O<sub>3</sub>-tolerant clone and by 32.7% in the O<sub>3</sub>-sensitive clone. At the same time, and in the same order, net photosynthesis rates were *increased* by 34.9%, 47.4%, 31.6% and 18.9%.

Possell *et al.* (2004) grew seedlings of English oak (*Quercus robur*), one to a mesocosm (16 cm diameter, 60 cm deep), in either fertilized or unfertilized soil in *solardomes* maintained at atmospheric CO<sub>2</sub> concentrations of either ambient or ambient plus 300 ppm for one full year, at the conclusion of which period they measured rates of isoprene emissions from the trees' foliage together with their rates of photosynthesis. In the unfertilized trees, this work revealed that the 300-ppm increase in the air's CO<sub>2</sub> concentration reduced isoprene emissions by 63% on a leaf area basis and 64% on a biomass basis, while in the fertilized trees the extra CO<sub>2</sub> reduced isoprene emissions by 70% on a leaf area basis and 74% on a biomass basis. In addition, the extra CO<sub>2</sub> boosted leaf photosynthesis rates by 17% in the unfertilized trees and 13% in the fertilized trees. At one and the same time, therefore, the CO<sub>2</sub>-enriched air of this experiment did a number of positive things. It (1) enhanced the photosynthetic rates of the trees' leaves, while it (2) reduced their rates of isoprene emission, which tends to (3) reduce the (a) lifetime and (b) atmospheric concentration of (i) methane and (ii) other radiatively active trace gases of the atmosphere, as well as (4) reduce the atmospheric concentration of radiatively-active and phytotoxic ozone, which accomplishments are rather astounding for a trace gas (CO<sub>2</sub>) that climate alarmists are trying to characterize as a *pollutant*.

Possell *et al.* (2005) performed multiple three-week-long experiments with two known isoprene-emitting herbaceous species (*Mucuna pruriens* and *Arundo donax*), which they grew in controlled environment chambers that were maintained at two different sets of day/night temperatures (29/24°C and 24/18°C) and atmospheric CO<sub>2</sub> concentrations characteristic of glacial (180 ppm), pre-industrial (280 ppm) and current (366 ppm) conditions, where canopy isoprene emission rates were measured on the final day of each experiment. In doing so, they obtained what they describe as "the first empirical evidence for the enhancement of isoprene production, on a unit leaf area basis, by plants that grew and developed in [a] CO<sub>2</sub>-depleted atmosphere," which results, in their words, "support earlier findings from short-term studies with woody species (Monson and Fall, 1989; Loreto and Sharkey, 1990)." Then, combining their emission rate data with those of Rosenstiel *et al.* (2003) for *Populus deltoides*, Centritto *et al.* (2004) for *Populus x euroamericana* and Scholefield *et al.* (2004) for *Phragmites australis*, they developed a single downward-trending isoprene emissions curve that stretches all the way from 180 to 1200 ppm CO<sub>2</sub>, where it asymptotically approaches a value that is *an order of magnitude less* than what it is at 180 ppm.

Working at the Biosphere 2 facility near Oracle, Arizona, USA, in enclosed ultraviolet light-depleted mesocosms (to minimize isoprene depletion by atmospheric oxidative reactions such as those involving OH), Pegoraro *et al.* (2005) studied the effects of atmospheric CO<sub>2</sub> enrichment (1200 ppm compared to an ambient concentration of 430 ppm) and drought on the emission of isoprene from cottonwood (*Populus deltoides* Bartr.) foliage and its absorption by the underlying soil for both well-watered and drought conditions. In doing so, they found that "under well-watered conditions in the agriforest stands, gross isoprene production (i.e., the total production flux minus the soil uptake) was inhibited by elevated CO<sub>2</sub> and the highest emission fluxes of isoprene were attained in the lowest CO<sub>2</sub> treatment." In more quantitative terms, it was determined that the elevated CO<sub>2</sub> treatment resulted in a 46% reduction in gross isoprene production. In addition, it was found that drought suppressed the isoprene sink



capacity of the soil beneath the trees, but that "the full sink capacity of dry soil was recovered within a few hours upon rewetting."

Putting a slightly negative slant on their findings, Pegoraro *et al.* suggested that "in future, potentially hotter, drier environments, higher CO<sub>2</sub> may not mitigate isoprene emission as much as previously suggested." However, we note that climate models generally predict an intensification of the hydrologic cycle in response to rising atmospheric CO<sub>2</sub> concentrations, and that the anti-transpirant effect of atmospheric CO<sub>2</sub> enrichment typically leads to *increases* in the moisture contents of soils beneath vegetation (see Soil Water Status Field Studies and Growth Chamber Studies in our Subject Index). Also, we note that over the latter decades of the 20th century, when climate alarmists claim the earth warmed at a rate and to a level that were *unprecedented over the past two millennia*, soil moisture data from all around the world tended to display *upward trends*. Robock *et al.* (2000), for example, developed a massive collection of soil moisture data from over 600 stations spread across a variety of climatic regimes, including the former Soviet Union, China, Mongolia, India and the United States, determining that "in contrast to predictions of summer desiccation with increasing temperatures, for the stations with the longest records, summer soil moisture in the top 1 m has increased while temperatures have risen." And in a subsequent study of "45 years of gravimetrically-observed plant available soil moisture for the top 1 m of soil, observed every 10 days for April-October for 141 stations from fields with either winter or spring cereals from the Ukraine for 1958-2002," Robock *et al.* (2005) discovered that these real-world observations "show a positive soil moisture trend for the entire period of observation," noting that "even though for the entire period there is a small upward trend in temperature and a downward trend in summer precipitation, the soil moisture still has an upward trend for both winter and summer cereals." Consequently, in a CO<sub>2</sub>-enriched world of the future, we likely will have the best of *both* aspects of isoprene activity: less production by vegetation and more consumption by soils.

Finally, we address the issue of how well models predict the response of isoprene emission to future global change. According to Monson *et al.* (2007) such predictions "probably contain large errors," which clearly need to be corrected. The reason for the errors, write the twelve researchers who conducted the study, is that "the fundamental logic of such models is that changes in NPP will produce more or less biomass capable of emitting isoprene, and changes in climate will stimulate or inhibit emissions per unit of biomass." Hence, as they continue, "these models tend to ignore the discovery that there are direct effects of changes in the atmospheric CO<sub>2</sub> concentration on isoprene emission that tend to work *in the opposite direction* [our italics] to that of stimulated NPP," as has clearly been indicated in the research studies described above. Furthermore, their results *showed*, in their words, "that growth in an atmosphere of elevated CO<sub>2</sub> inhibited the emission of isoprene at levels that *completely compensate* [our italics] for possible increases in emission due to increases in aboveground NPP."

In lamenting this sorry state of global-change modeling, Monson *et al.* say that, "to a large extent, the modeling has 'raced ahead' of our mechanistic understanding of how isoprene emissions will respond to the fundamental drivers of global change," and that "without

inclusion of these effects in the current array of models being used to predict changes in atmospheric chemistry due to global change, one has to question the relevance of the predictions."

Fast forward a year later and we come to the study of Arneth *et al.* (2008), who used a mechanistic isoprene-dynamic vegetation model of European woody vegetation to "investigate the interactive effects of climate and CO<sub>2</sub> concentration on forest productivity, species composition, and isoprene emissions for the periods 1981-2000 and 2081-2100," which *included* a parameterization of the now-well-established direct CO<sub>2</sub>-isoprene inhibition phenomenon we have described in the papers above. Not surprisingly, with the inclusion of this parameterization, the results of the study indicate that "across the model domain," the CO<sub>2</sub>-isoprene inhibition effect "has the potential to offset the stimulation of [isoprene] emissions that could be expected from warmer temperatures and from the increased productivity and leaf area of emitting vegetation."

In view of these many encouraging findings presented above, it would thus appear that the ongoing rise in the atmosphere's CO<sub>2</sub> concentration will lead to ever greater reductions in atmospheric isoprene concentrations; and as noted in the introductory paragraph of this section, such a consequence would be very welcome news for humanity and nature alike. Although these beneficial findings are important, we find no mention of them in the IPCC or other assessments on earth's rising atmospheric carbon dioxide concentration.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/i/isoprene.php>.

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### 6.7.2. Microorganisms

Plants grown in CO<sub>2</sub>-enriched atmospheres nearly always exhibit increased photosynthetic rates and biomass production. Due to this productivity enhancement, more plant material is typically added to soils from root growth, turnover and exudation, as well as from leaves and stems following their abscission and falling to the ground during senescence. Such additions of carbon onto and into soils often serve as the only carbon source for supporting the development and growth of microorganisms in terrestrial habitats. Thus, it is important to understand how CO<sub>2</sub>-induced increases in plant growth affect microorganisms, another important topic often omitted from discussion by climate alarmists.

Several studies have shown that atmospheric CO<sub>2</sub> enrichment does not significantly impact soil microorganisms. Zak *et al.* (2000), for example, observed no significant differences in soil microbial biomass beneath aspen seedlings grown at 350 and 700 ppm CO<sub>2</sub> after 2.5 years of differential treatment. Likewise, in the cases of Griffiths *et al.* (1998) and Insam *et al.* (1999), neither research team reported any changes in microbial community structure beneath

ryegrass and artificial tropical ecosystems, respectively, after subjecting them to atmospheric CO<sub>2</sub> enrichment.

Other studies, however, have found that elevated CO<sub>2</sub> can significantly impact soil microorganisms. Van Ginkel and Gorissen (1998), for example, observed that three months of elevated CO<sub>2</sub> exposure (700 ppm) increased soil microbial biomass beneath ryegrass plants by 42% relative to that produced under ambient CO<sub>2</sub> conditions, as did Van Ginkel *et al.* (2000). Likewise, soil microbial biomass was reported to increase by 15% beneath agricultural fields subjected to a two-year wheat-soybean crop rotation (Islam *et al.*, 2000); and in a study by Marilley *et al.* (1999), atmospheric CO<sub>2</sub> enrichment significantly increased bacterial numbers in the rhizospheres beneath ryegrass and white clover monocultures. Similarly, Lussenhop *et al.* (1998) reported CO<sub>2</sub>-induced increases in the amounts of bacteria, protozoa, and microarthropods in soils that had supported regenerating poplar tree cuttings for five months. In addition, Hungate *et al.* (2000) reported that twice-ambient CO<sub>2</sub> concentrations significantly increased the biomass of active fungal organisms and flagellated protozoa beneath serpentine and sandstone grasslands after four years of treatment exposure.

In taking a closer look at the study of Marilley *et al.* (1999), it is evident that elevated CO<sub>2</sub> caused shifts in soil microbial populations. In soils beneath their leguminous white clover, for example, elevated CO<sub>2</sub> favored shifts towards *Rhizobium* bacterial species, which likely increased nitrogen availability - via nitrogen fixation - to support enhanced plant growth. However, in soils beneath non-leguminous ryegrass monocultures, which do not form symbiotic relationships with *Rhizobium* species, elevated CO<sub>2</sub> favored shifts towards *Pseudomonas* species, which likely acquired nutrients to support enhanced plant growth through mechanisms other than nitrogen fixation. Nonetheless, in both situations, the authors observed CO<sub>2</sub>-induced shifts in bacterial populations that would likely optimize nutrient acquisition for specific host plant species.

In a non-related study, Montealegre *et al.* (2000) reported that elevated CO<sub>2</sub> acted as a selective agent among 120 different isolates of *Rhizobium* growing beneath white clover plants. Specifically, when bacterial strains favored by ambient and elevated CO<sub>2</sub> concentrations were mixed together and grown with white clover at an atmospheric CO<sub>2</sub> concentration of 600 ppm, 17% more root nodules were formed by isolates previously determined to be favored by elevated CO<sub>2</sub>.

In the interesting study of Hu *et al.* (2001), fertile sandstone grasslands subjected to five years of twice-ambient CO<sub>2</sub> concentrations exhibited increased soil microbial biomass while simultaneously enhancing plant nitrogen uptake. The net effect of these phenomena reduced nitrogen availability for microbial use, which consequently decreased microbial respiration and, hence, microbial decomposition. Consequently, these ecosystems displayed CO<sub>2</sub>-induced increases in net carbon accumulation. Similarly, Williams *et al.* (2000) reported that microbial biomass carbon increased by 4% in a tallgrass prairie after five years exposure to twice-ambient CO<sub>2</sub> concentrations, which contributed to a total soil carbon enhancement of 8%.

In another study, Johnson *et al.* (2002) presented evidence that elevated levels of atmospheric CO<sub>2</sub> will also enhance soil microbes in the face of the enhanced receipt of solar ultraviolet-B radiation that would be expected to occur in response to a 15% depletion of the earth's stratospheric ozone layer. Johnson *et al.* conducted their landmark work on experimental plots of subarctic heath located close to the Abisko Scientific Research Station in Swedish Lapland (68.35°N, 18.82°E). The plots they studied were composed of open canopies of *Betula pubescens* ssp. *czerepanovii* and dense dwarf-shrub layers containing scattered herbs and grasses. For a period of five years, the scientists exposed the plots to factorial combinations of UV-B radiation - ambient and that expected to result from a 15% stratospheric ozone depletion - and atmospheric CO<sub>2</sub> concentration - ambient (around 365 ppm) and enriched (around 600 ppm) - after which they determined the amounts of microbial carbon (C<sub>mic</sub>) and nitrogen (N<sub>mic</sub>) in the soils of the plots.

When the plots were exposed to the enhanced UV-B radiation level expected to result from a 15% depletion of the planet's stratospheric ozone layer, the researchers found that the amount of C<sub>mic</sub> in the soil was reduced to only 37% of what it was at the ambient UV-B level when the air's CO<sub>2</sub> content was maintained at the ambient concentration. When the UV-B increase was accompanied by the CO<sub>2</sub> increase, however, not only was there *not* a decrease in C<sub>mic</sub>, there was an actual *increase* of fully 37%.

The story with respect to N<sub>mic</sub> was both similar and different at one and the same time. In this case, when the plots were exposed to the enhanced level of UV-B radiation, the amount of N<sub>mic</sub> in the soil experienced a 69% *increase* when the air's CO<sub>2</sub> content was maintained at the ambient concentration. When the UV-B increase was accompanied by the CO<sub>2</sub> increase, however, N<sub>mic</sub> rose even more, experiencing a whopping 138% increase.

These findings, in the words of Johnson *et al.*, "may have far-reaching implications ... because the productivity of many semi-natural ecosystems is limited by N (Ellenberg, 1988)." Hence, the 138% increase in soil microbial N observed in this study to accompany a 15% reduction in stratospheric ozone and a concomitant 64% increase in atmospheric CO<sub>2</sub> concentration (experienced in going from 365 ppm to 600 ppm) should do wonders in enhancing the input of plant litter to the soils of these ecosystems, which phenomenon represents the first half of the carbon sequestration process, i.e., the carbon input stage.

With respect to the second stage of *keeping* as much of that carbon as possible in the soil, Johnson *et al.* note that "the capacity for subarctic semi-natural heaths to act as major sinks for fossil fuel-derived carbon dioxide is [also] likely to be critically dependent on the supply of N." Indeed, in a previous essay in this series, wherein we discussed the findings of the literature review of Berg and Matzner (1997), we found that such is truly the case. With more nitrogen in the soil, the long-term storage of carbon is significantly enhanced, as more litter is chemically transformed into humic substances when nitrogen is more readily available; and these resulting more recalcitrant carbon compounds can be successfully stored in the soil for many millennia.

In summation, it is clear from the published literature that as the CO<sub>2</sub> content of the air continues to rise, earth's vegetation will likely respond with increasing photosynthetic rates and biomass production. As a consequence of these phenomena, more organic carbon will be returned to the soil where it will be utilized by microbial organisms to maintain or increase their population numbers, biomass and heterotrophic activities (Weihong *et al.*, 2000; Arnone and Bohlen, 1998). Moreover, it is conceivable that shifts in microbial community structure may occur that will favor the intricate relationships that currently exist between leguminous and non-leguminous plants and the specific microorganisms upon which they depend.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/m/microorganisms.php>.

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### 6.7.3. Nitrogen Use Efficiency

Long-term exposure to elevated atmospheric CO<sub>2</sub> concentrations often, but not always, elicits photosynthetic acclimation or down regulation in plants, which is typically accompanied by reduced amounts of rubisco and/or other photosynthetic proteins that are typically present in excess amounts in ambient air. As a consequence of this latter phenomenon, foliar nitrogen concentrations often decrease with atmospheric CO<sub>2</sub> enrichment, as nitrogen is mobilized out of leaves and into other areas of the plant to increase its availability for enhancing sink development or stimulating other nutrient-limited processes.

In reviewing the literature in this area, one quickly notices that in spite of the fact that photosynthetic acclimation has occurred, CO<sub>2</sub>-enriched plants nearly always display rates of photosynthesis that are greater than those of control plants exposed to ambient air. Consequently, photosynthetic nitrogen-use efficiency, i.e., the amount of carbon converted into sugars during the photosynthetic process per unit of leaf nitrogen, often increases dramatically in CO<sub>2</sub>-enriched plants.



In the study of Davey *et al.* (1999), for example, CO<sub>2</sub>-induced reductions in foliar nitrogen contents and concomitant increases in photosynthetic rates led to photosynthetic nitrogen-use efficiencies in the CO<sub>2</sub>-enriched (to 700 ppm CO<sub>2</sub>) grass *Agrostis capillaris* that were 27 and 62% greater than those observed in control plants grown at 360 ppm CO<sub>2</sub> under moderate and low soil nutrient conditions, respectively. Similarly, elevated CO<sub>2</sub> enhanced photosynthetic nitrogen-use efficiencies in *Trifolium repens* by 66 and 190% under moderate and low soil nutrient conditions, respectively, and in *Lolium perenne* by 50%, regardless of soil nutrient status. Other researchers have found comparable CO<sub>2</sub>-induced enhancements of photosynthetic nitrogen-use efficiency in wheat (Osborne *et al.*, 1998) and in *Leucadendron* species (Midgley *et al.*, 1999).

In some cases, researchers report nitrogen-use efficiency in terms of the amount of biomass produced per unit of plant nitrogen. Niklaus *et al.* (1998), for example, reported that intact swards of CO<sub>2</sub>-enriched calcareous grasslands grown at 600 ppm CO<sub>2</sub> attained total biomass values that were 25% greater than those of control swards exposed to ambient air while extracting the same amount of nitrogen from the soil as ambiently-grown swards. Similar results have been reported for strawberry by Deng and Woodward (1998), who noted that the growth nitrogen-use efficiencies of plants grown at 560 ppm CO<sub>2</sub> were 23 and 17% greater than those of ambiently-grown plants simultaneously subjected to high and low soil nitrogen availability, respectively.

In conclusion, the scientific literature indicates that as the air's CO<sub>2</sub> content continues to rise, earth's plants will likely respond by reducing the amount of nitrogen invested in rubisco and other photosynthetic proteins, while still maintaining enhanced rates of photosynthesis, which consequently should increase their photosynthetic nitrogen-use efficiencies. In addition, enhanced rates of photosynthetic carbon uptake invariably lead to greater biomass production, which often occurs without increasing soil nitrogen uptake and thus enhances growth nitrogen-use efficiency as well. Hence, as overall plant nitrogen-use efficiency increases with the ongoing rise in the atmosphere's CO<sub>2</sub> concentration, it is likely that plants will grow ever better on soils containing less-than-optimal levels of this important soil nutrient.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/n/nitrogenefficiency.php>.

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#### 6.7.4. Nutrient Acquisition

Most species of plants respond to increases in the air's CO<sub>2</sub> content by displaying enhanced rates of photosynthesis and biomass production. Oftentimes, the resulting growth stimulation is preferentially expressed belowground, thereby causing significant increases in fine-root numbers and surface area. This phenomenon tends to increase total nutrient uptake under CO<sub>2</sub>-enriched conditions, which further stimulates plant growth and development. In this summary, we thus review how the acquisition of plant nutrients - primarily nitrate and phosphate - is impacted by atmospheric CO<sub>2</sub> enrichment. We do not discuss the effects of elevated CO<sub>2</sub> on nitrogen fixation, however, as we address this subject elsewhere on our website (see Nitrogen Fixation).

In the study of Zak *et al.* (2000), aspen seedlings grown for 2.5 years at twice-ambient CO<sub>2</sub> concentrations displayed an average total seedling nitrogen content that was 13% greater than that displayed by control seedlings grown in ambient air, in spite of an average reduction in tissue nitrogen concentration of 18%. Thus, elevated CO<sub>2</sub> enhanced total nitrogen uptake from the soil, even though tissue nitrogen concentrations in the CO<sub>2</sub>-enriched plants were diluted by the enhanced biomass of the much larger CO<sub>2</sub>-enriched seedlings.

On a per-unit-biomass basis, Smart *et al.* (1998) noted there were no differences in the total amounts of nitrogen within CO<sub>2</sub>-enriched and ambiently-grown wheat seedlings after three weeks of exposure to atmospheric CO<sub>2</sub> concentrations of 360 and 1,000 ppm. Nevertheless, the CO<sub>2</sub>-enriched seedlings exhibited greater rates of soil nitrate extraction than did the ambiently-grown plants. Similarly, BassiriRad *et al.* (1998) reported that a doubling of the atmospheric CO<sub>2</sub> concentration doubled the uptake rate of nitrate in the C<sub>4</sub> grass *Bouteloua eriopoda*. However, they also reported that elevated CO<sub>2</sub> had no effect on the rate of nitrate uptake in *Prosopis*, and that it actually decreased the rate of nitrate uptake by 55% in *Larrea*. Nonetheless, atmospheric CO<sub>2</sub> enrichment increased total biomass in these two species by 55 and 69%, respectively. Thus, although the uptake rate of this nutrient was depressed under elevated CO<sub>2</sub> conditions in the latter species, the much larger CO<sub>2</sub>-enriched plants likely still extracted more total nitrate from the soil than did the ambiently-grown plants of the experiment.

It is also interesting to note that Nasholm *et al.* (1998) determined that trees, grasses and shrubs can all absorb significant amounts of organic nitrogen from soils. Thus, plants do not have to wait for the mineralization of organic nitrogen before they extract the nitrogen they need from soils to support their growth and development. Hence, the forms of nitrogen removed from soils by plants (nitrate vs. ammonium) and their abilities to remove different forms may not be as important as was once thought.

With respect to the uptake of phosphate, Staddon *et al.* (1999) reported that *Plantago lanceolata* and *Trifolium repens* plants grown at 650 ppm CO<sub>2</sub> for 2.5 months exhibited total plant phosphorus contents that were much greater than those displayed by plants grown at 400 ppm CO<sub>2</sub>, due to the fact that atmospheric CO<sub>2</sub> enrichment significantly enhanced plant biomass. Similarly, Rouhier and Read (1998) reported that enriching the air around *Plantago lanceolata* plants with an extra 190 ppm of CO<sub>2</sub> for a period of three months led to increased uptake of phosphorus and greater tissue phosphorus concentrations than were observed in plants growing in ambient air.

Greater uptake of phosphorus can also occur due to CO<sub>2</sub>-induced increases in root absorptive surface area or enhancements in specific enzyme activities. In addressing the first of these phenomena, BassiriRad *et al.* (1998) reported that a doubling of the atmospheric CO<sub>2</sub> concentration significantly increased the belowground biomass of *Bouteloua eriopoda* and doubled its uptake rate of phosphate. However, elevated CO<sub>2</sub> had no effect on uptake rates of phosphate in *Larrea* and *Prosopis*. Because the CO<sub>2</sub>-enriched plants grew so much bigger, however, they still removed more phosphate from the soil on a per-plant basis. With respect to the second phenomenon, phosphatase - which is the primary enzyme responsible for the conversion of organic phosphate into usable inorganic forms - had its activity increased by 30 to 40% in wheat seedlings growing at twice-ambient CO<sub>2</sub> concentrations (Barrett *et al.*, 1998).

In summary, as the CO<sub>2</sub> content of the air increases, the experimental data that have been accumulated to date suggest that much of earth's vegetation will likely display increases in biomass; and there is considerable evidence suggestive of the further likelihood that the larger plants thereby produced will develop more extensive root systems and extract enhanced amounts of mineral nutrients from the soils in which they are rooted.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/n/nutrientacquis.php>.

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### 6.7.5. Pathogens

As the air's CO<sub>2</sub> content continues to rise, it is natural to wonder - and important to determine - how this phenomenon may impact plant-pathogen interactions. One thing we know about the subject is that atmospheric CO<sub>2</sub> enrichment nearly always enhances photosynthesis, which commonly leads to increased plant production of carbon-based secondary compounds, including lignin and various phenolics, both of which substances tend to increase plant resistance to pathogen attack.

Enlarging upon this topic, Chakraborty and Datta (2003) report that "changes in plant physiology, anatomy and morphology that have been implicated in increased resistance or [that] can potentially enhance host resistance at elevated CO<sub>2</sub> include: increased net photosynthesis allowing mobilization of resources into host resistance (Hibberd *et al.*, 1996a.); reduced stomatal density and conductance (Hibberd *et al.*, 1996b); greater accumulation of carbohydrates in leaves; more waxes, extra layers of epidermal cells and increased fibre content (Owensby, 1994); production of papillae and accumulation of silicon at penetration sites (Hibberd *et al.*, 1996a); greater number of mesophyll cells (Bowes, 1993); and increased biosynthesis of phenolics (Hartley *et al.*, 2000), among others."

Adding to this impressive list, Chakraborty and Datta elucidated yet another way in which atmospheric CO<sub>2</sub> enrichment may tip the scales in favor of plants in a study of the aggressiveness of the fungal anthracnose pathogen *Colletotrichum gloeosporioides*, wherein they inoculated two isolates of the pathogen onto two cultivars of the tropical pasture legume *Stylosanthes scabra* (Fitzroy, which is susceptible to the fungal pathogen, and Seca, which is

more resistant) over the course of 25 sequential infection cycles at ambient (350 ppm) and elevated (700 ppm) atmospheric CO<sub>2</sub> concentrations in controlled environment chambers. This protocol revealed that "at twice-ambient CO<sub>2</sub> the overall level of aggressiveness of the two [pathogen] isolates was significantly reduced on both [host] cultivars." In addition, they say that "as shown previously (Chakraborty *et al.*, 2000), the susceptible Fitzroy develops a level of resistance to anthracnose at elevated CO<sub>2</sub>, but resistance in Seca remains largely unchanged." Simultaneously, however, pathogen *fecundity* was found to *increase* at twice-ambient CO<sub>2</sub>. Of this finding, they report that their results "concur with the handful of studies that have demonstrated increased pathogen fecundity at elevated CO<sub>2</sub> (Hibberd *et al.*, 1996a; Klironomos *et al.*, 1997; Chakraborty *et al.*, 2000)." How this happened in the situation they investigated, as they describe it, is that the overall increase in fecundity at high CO<sub>2</sub> "is a reflection of the altered canopy environment," wherein "the 30% larger *S. scabra* plants at high CO<sub>2</sub> (Chakraborty *et al.*, 2000) makes the canopy microclimate more conducive to anthracnose development."

In view of the opposing changes induced in pathogen behavior by elevated levels of atmospheric CO<sub>2</sub> in this specific study - reduced aggressiveness but increased fecundity - it is difficult to know the ultimate outcome of atmospheric CO<sub>2</sub> enrichment for the pathogen-host relationship. More research, especially under realistic field conditions, will be needed to clarify the situation; and, of course, different results are likely to be observed for different pathogen-host associations. What is more, results could also differ under different climatic conditions. Nevertheless, the large number of ways in which elevated CO<sub>2</sub> has been demonstrated to increase plant resistance to pathogen attack suggests that plants may well gain the advantage over pathogens as the air's CO<sub>2</sub> content continues to climb in the years ahead; and in the paragraphs that follow, we review the results of a number of studies that support this assessment of the issue.

A good place to begin is the study of McElrone *et al.* (2005) who "assessed how elevated CO<sub>2</sub> affects a foliar fungal pathogen, *Phyllosticta minima*, of *Acer rubrum* [red maple] growing in the understory at the Duke Forest free-air CO<sub>2</sub> enrichment experiment in Durham, North Carolina, USA ... in the 6th, 7th, and 8th years of the CO<sub>2</sub> exposure." Surveys conducted in those years, in their words, "revealed that elevated CO<sub>2</sub> [to 200 ppm above ambient] significantly reduced disease incidence, with 22%, 27% and 8% fewer saplings and 14%, 4%, and 5% fewer leaves infected per plant in the three consecutive years, respectively." In addition, they report that the elevated CO<sub>2</sub> "also significantly reduced disease severity in infected plants in all years (e.g. mean lesion area reduced 35%, 50%, and 10% in 2002, 2003, and 2004, respectively)."

With respect to identifying the underlying mechanism or mechanisms that produced these beneficent consequences, thinking it could have been a direct deleterious effect of elevated CO<sub>2</sub> on the fungal pathogen, McElrone *et al.* performed some side experiments in controlled environment chambers. However, they found that the elevated CO<sub>2</sub> benefited the fungal pathogen as well as the red maple saplings, observing that "exponential growth rates of *P. minima* were 17% greater under elevated CO<sub>2</sub>." And they obtained similar results when they repeated the *in vitro* growth analysis two additional times in different growth chambers.

Taking another tack when "scanning electron micrographs verified that conidia germ tubes of *P. minima* infect *A. rubrum* leaves by entering through the stomata," the researchers turned their attention to the pathogen's mode of entry into the saplings' foliage. In this investigation they found that both stomatal size and density were unaffected by atmospheric CO<sub>2</sub> enrichment, but that "stomatal conductance was reduced by 21-36% under elevated CO<sub>2</sub>, providing smaller openings for infecting germ tubes." In addition, they concluded that reduced disease severity under elevated CO<sub>2</sub> was also likely due to altered leaf chemistry, as elevated CO<sub>2</sub> increased total leaf phenolic concentrations by 15% and tannin concentrations by 14%.

Because the phenomena they found to be important in reducing the amount and severity of fungal pathogen infection (leaf spot disease) of red maple have been demonstrated to be operative in most other plants as well, McElrone *et al.* say these CO<sub>2</sub>-enhanced leaf defensive mechanisms "may be prevalent in many plant pathosystems where the pathogen targets the stomata." Indeed, they state that their results "provide concrete evidence for a potentially generalizable mechanism to predict disease outcomes in other pathosystems under future climatic conditions." And because of their insightful work, that future is looking particularly bright in terms of the never-ending struggle between earth's plants and the pathogens that prey upon them. Although elevated CO<sub>2</sub> helps *both* sides of the conflict, it helps plants *more* and in *more ways*.

Malmstrom and Field (1997) grew individual oat plants for two months in pots within phytocells maintained at CO<sub>2</sub> concentrations of 350 and 700 ppm, while a third of each CO<sub>2</sub> treatment's plants were infected with the barley yellow dwarf virus (BYDV), which plagues more than 150 plant species worldwide, including all major cereal crops. They found that the elevated CO<sub>2</sub> stimulated net photosynthesis rates in all plants, but with the greatest increase occurring in diseased individuals (48% vs. 34%). In addition, atmospheric CO<sub>2</sub> enrichment decreased stomatal conductance by 34% in healthy plants, but by 50% in infected ones, thus reducing transpirational water losses more in infected plants. Together, these two phenomena contributed to a CO<sub>2</sub>-induced doubling of the instantaneous water-use efficiency of healthy control plants, but to a much larger 2.7-fold increase in diseased plants. Thus, although BYDV infection did indeed reduce overall plant biomass production, the growth response to elevated CO<sub>2</sub> was greatest in the diseased plants. After 60 days of CO<sub>2</sub> enrichment, for example, total plant biomass increased by 36% in infected plants, while it increased by only 12% in healthy plants. In addition, while elevated CO<sub>2</sub> had little effect on root growth in healthy plants, it increased root biomass in infected plants by up to 60%. In their concluding remarks, therefore, Malmstrom and Field say that CO<sub>2</sub> enrichment "may reduce losses of infected plants to drought" and "may enable diseased plants to compete better with healthy neighbors."

Tiedemann and Firsching (2000) grew spring wheat from germination to maturity in controlled environment chambers maintained at either ambient (377 ppm) or enriched (612 ppm) atmospheric CO<sub>2</sub> concentrations and either ambient (20 ppb) or enriched (61 ppb) atmospheric ozone (O<sub>3</sub>) concentrations, while half of the plants in each of the four resulting treatments were inoculated with a leaf rust-causing pathogen. These procedures revealed that the *percent of*

*leaf area* infected by rust in inoculated plants was largely unaffected by atmospheric CO<sub>2</sub> enrichment but strongly reduced by elevated O<sub>3</sub>. With respect to *photosynthesis*, elevated CO<sub>2</sub> increased rates in inoculated plants by 20 and 42% at ambient and elevated O<sub>3</sub> concentrations, respectively. Although inoculated plants produced lower yields than non-inoculated plants, atmospheric CO<sub>2</sub> enrichment still stimulated yield in infected plants, increasing it by fully 57% at high O<sub>3</sub>. Consequently, the beneficial effects of elevated CO<sub>2</sub> on wheat photosynthesis and yield continue to be expressed in the presence of both O<sub>3</sub> and pathogenic stresses.

In another joint CO<sub>2</sub>/O<sub>3</sub> study, Percy *et al.* (2002) grew the most widely distributed North American tree species - trembling aspen - in twelve 30-m-diameter FACE rings near Rhinelander, Wisconsin, USA in air maintained at ambient CO<sub>2</sub> and O<sub>3</sub> concentrations, ambient O<sub>3</sub> and elevated CO<sub>2</sub> (560 ppm during daylight hours), ambient CO<sub>2</sub> and elevated O<sub>3</sub> (46.4-55.5 ppb during daylight hours), and elevated CO<sub>2</sub> and O<sub>3</sub> over the period of each growing season from 1998 through 2001. Throughout this experiment they assessed a number of the young trees' growth characteristics, as well as their responses to poplar leaf rust (*Melampsora medusae*), which they say "is common on aspen and belongs to the most widely occurring group of foliage diseases." Their work revealed that elevated CO<sub>2</sub> alone did not alter rust occurrence, but that elevated O<sub>3</sub> alone increased it by nearly fourfold. When applied together, however, elevated CO<sub>2</sub> reduced the enhancement of rust development caused by elevated O<sub>3</sub> from nearly fourfold to just over twofold.

Jwa and Walling (2001) grew tomato plants in hydroponic culture for eight weeks in controlled environment chambers maintained at atmospheric CO<sub>2</sub> concentrations of 350 and 700 ppm. At week five of their study, half of the plants growing in each CO<sub>2</sub> concentration were infected with the fungal pathogen *Phytophthora parasitica*, which attacks plant roots and induces water stress that ultimately decreases plant growth and yield. This infection procedure ultimately reduced total plant biomass by nearly 30% at both atmospheric CO<sub>2</sub> concentrations. However, the elevated CO<sub>2</sub> treatment increased the total biomass of healthy and infected plants by the same percentage, so that infected tomato plants grown at 700 ppm CO<sub>2</sub> exhibited biomass values similar to those of healthy tomato plants grown at 350 ppm CO<sub>2</sub>. Consequently, atmospheric CO<sub>2</sub> enrichment *completely counterbalanced* the negative effects of *Phytophthora parasitica* infection on tomato productivity.

Pangga *et al.* (2004) grew well-watered and fertilized pencilflower (cultivar Fitzroy) seedlings - an important legume crop susceptible to anthracnose disease caused by *Colletotrichum gloeosporioides* - within a controlled environment facility maintained at atmospheric CO<sub>2</sub> concentrations of either 350 or 700 ppm, where they inoculated six-, nine- and twelve-week-old plants with conidia of *C. gloeosporioides*. Then, ten days after inoculation, they counted the anthracnose lesions on the plants and classified them as either resistant or susceptible. In doing so, they found that "the mean number of susceptible, resistant, and total lesions per leaf averaged over the three plant ages was significantly ( $P < 0.05$ ) greater at 350 ppm than at 700 ppm CO<sub>2</sub>, reflecting the development of a level of resistance in susceptible cv. Fitzroy at high CO<sub>2</sub>." In fact, with respect to plants inoculated at twelve weeks of age, they say that those grown "at 350 ppm had 60 and 75% more susceptible and resistant lesions per leaf,

respectively, than those [grown] at 700 ppm CO<sub>2</sub>." Last of all, the Australian scientists say their work "clearly shows that at 350 ppm overall susceptibility of the canopy increases with increasing age because more young leaves are produced on secondary and tertiary branches of the more advanced plants." However, they report that "at 700 ppm CO<sub>2</sub>, infection efficiency did not increase with increasing plant age despite the presence of many more young leaves in the enlarged canopy," which finding, in their words, "points to reduced pathogen efficiency or an induced partial resistance to anthracnose in Fitzroy at 700 ppm CO<sub>2</sub>."

Finally, according to Plesl *et al.* (2007), "potato late blight caused by the oomycete *Phytophthora infestans* (Mont.) de Bary is the most devastating disease of potato worldwide," adding that "infection occurs through leaves and tubers followed by a rapid spread of the pathogen finally causing destructive necrosis." In an effort to ascertain the effects of atmospheric CO<sub>2</sub> enrichment on this pathogen, Plesl *et al.* grew individual well watered and fertilized plants of the potato cultivar Indira in 3.5-liter pots filled with a 1:2 mixture of soil and "Fruhstorfer T-Erde" in controlled-environment chambers maintained at atmospheric CO<sub>2</sub> concentrations of either 400 or 700 ppm. Four weeks after the start of the experiment, the first three fully-developed pinnate leaves were cut from the plants and inoculated with zoospores of *P. infestans* in Petri dishes containing water-agar, after which their symptoms were evaluated daily via comparison with control leaves that were similarly treated but unexposed to the pathogen.

Results of the German researchers analysis revealed that the 300 ppm increase in CO<sub>2</sub> "dramatically reduced symptom development," including *extent of necrosis* (down by 44% four days after inoculation and 65% five days after inoculation), *area of sporulation* (down by 100% four days after inoculation and 61% five days after inoculation), and *sporulation intensity* (down by 73% four days after inoculation and 17% five days after inoculation). Thus, Plesl *et al.* conclude that their results "clearly demonstrated that the potato cultivar Indira, which under normal conditions shows a high susceptibility to *P. infestans*, develops resistance against this pathogen after exposure to 700 ppm CO<sub>2</sub>," noting that "this finding agrees with results from Ywa *et al.* (1995), who reported an increased tolerance of tomato plants to *Phytophthora* root rot when grown at elevated CO<sub>2</sub>." These similar observations bode well for both potato and tomato cultivation in a CO<sub>2</sub>-enriched world of the future.

In conclusion, the balance of evidence obtained to date appears to demonstrate an enhanced ability of plants to withstand pathogen attacks in CO<sub>2</sub>-enriched as opposed to ambient-CO<sub>2</sub> air. Hence, as the atmosphere's CO<sub>2</sub> concentration continues to rise in the years, decades and centuries to come, earth's vegetation should fare ever better in its eternal battle to better withstand the ravages that have historically been inflicted upon it by a myriad of debilitating plant diseases.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/p/pathogens.php>.



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#### 6.7.6. Parasites

Parasitic plants obtain energy, water and nutrients from their host plants and cause widespread reductions in harvestable yields around the globe. Hence, it is important to understand how rising atmospheric CO<sub>2</sub> levels may impact the growth of parasitic plants and the relationships that exist between them and their host plants. Here, we review the findings of several papers that have investigated this important subject.

Matthies and Egli (1999) grew *Rhinanthus alectorolophus* (a widely distributed parasitic plant of Central Europe) for a period of two months on the grass *Lolium perenne* and the legume *Medicago sativa* in pots placed within open-top chambers maintained at atmospheric CO<sub>2</sub> concentrations of 375 and 590 ppm, half of which pots were fertilized to produce an optimal soil nutrient regime and half of which were unfertilized. At *low* nutrient supply, they found that atmospheric CO<sub>2</sub> enrichment *decreased* mean parasite biomass by an average of 16%, while at *high* nutrient supply it *increased* parasite biomass by an average of 123%. Nevertheless, the extra 215 ppm of CO<sub>2</sub> increased host plant biomass in both situations: by 29% under high soil nutrition and by 18% under low soil nutrition.

Dale and Press (1999) infected white clover (*Trifolium repens*) plants with *Orobanche minor* (a parasitic weed that primarily infects leguminous crops in the United Kingdom and the Middle East) and exposed them to atmospheric CO<sub>2</sub> concentrations of either 360 or 550 ppm for 75 days in controlled-environment growth cabinets. The elevated CO<sub>2</sub> in this study had no effect on the total biomass of parasite per host plant, nor did it impact the number of parasites per host plant or the time to parasitic attachment to host roots. On the other hand, whereas infected host plants growing in ambient air produced 47% less biomass than uninfected plants growing in ambient air, infected plants growing at 550 ppm CO<sub>2</sub> exhibited final dry weights that were only 20% less than those displayed by uninfected plants growing in the CO<sub>2</sub>-enriched air,

indicative of a significant CO<sub>2</sub>-induced partial alleviation of parasite-induced biomass reductions in the white clover host plants.

Watling and Press (1997) infected several C<sub>4</sub> sorghum plants with *Striga hermonthica* and *Striga asiatica* (parasitic C<sub>3</sub> weeds of the semi-arid tropics that infest many grain crops) and grew them, along with uninfected control plants, for approximately two months in controlled-environment cabinets maintained at atmospheric CO<sub>2</sub> concentrations of 350 and 700 ppm. In the absence of parasite infection, the extra 350 ppm of CO<sub>2</sub> increased sorghum biomass by approximately 36%. When infected with *S. hermonthica*, however, the sorghum plants grown at ambient and elevated CO<sub>2</sub> concentrations only produced 32 and 43% of the biomass displayed by their respective uninfected controls. Infection with *S. asiatica* was somewhat less stressful and led to host biomass production that was about half that of uninfected controls in both ambient and CO<sub>2</sub>-enriched air. The end result was that the doubling of the air's CO<sub>2</sub> content employed in this study increased sorghum biomass by 79% and 35% in the C<sub>4</sub> sorghum plants infected with *S. hermonthica* and *S. asiatica*, respectively.

Hwangbo *et al.* (2003) grew Kentucky Bluegrass (*Poa pratensis* L.) with and without infection by the C<sub>3</sub> chlorophyllous parasitic angiosperm *Rhinanthus minor* L. (a facultative hemiparasite found in natural and semi-natural grasslands throughout Europe) for eight weeks in open-top chambers maintained at ambient and elevated (650 ppm) CO<sub>2</sub> concentrations. At the end of the study, the parasite's biomass (when growing on its host) was 47% greater in the CO<sub>2</sub>-enriched chambers, while its host exhibited only a 10% CO<sub>2</sub>-induced increase in biomass in the parasite's absence but a nearly doubled 19% increase when infected by it.

Watling and Press (2000) grew upland rice (*Oryza sativa* L.) in pots in controlled-environment chambers maintained at 350 and 700 ppm CO<sub>2</sub> in either the presence or absence of the root parasite *S. hermonthica* for a period of 80 days after sowing, after which time the plants were harvested and weighed. In ambient air, the presence of the parasite reduced the biomass of the rice to only 35% of what it was in the absence of the parasite; whereas in air enriched with CO<sub>2</sub> the presence of the parasite reduced the biomass of infected plants to but 73% of what it was in the absence of the parasite.

In summary, these several observations suggest that the rising CO<sub>2</sub> content of the air can have wide and variable effects on parasitic plants, ranging from negative to positive growth responses, depending upon soil nutrition and host plant specificity. With respect to the infected host plants, elevated CO<sub>2</sub> generally tends to reduce the negative effects of parasitic infection, so that infected host plants continue to exhibit positive growth responses to elevated CO<sub>2</sub>. Thus, it is likely that whatever the scenario with regard to parasitic infection, host plants will fare better under higher atmospheric CO<sub>2</sub> conditions than they do currently.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/p/parasites.php>.

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### 6.7.7. Roots

In reviewing the scientific literature pertaining to atmospheric CO<sub>2</sub> enrichment effects on belowground plant growth and development, Weihong *et al.* (2000) briefly summarize what is known about this subject. They report that atmospheric CO<sub>2</sub> enrichment typically enhances the growth rates of roots, especially those of fine roots, and that CO<sub>2</sub>-induced increases in root production eventually lead to increased carbon inputs to soils, due to enhanced root turnover and exudation of various organic carbon compounds, which can potentially lead to greater soil carbon sequestration. In addition, they note that increased soil carbon inputs stimulate the growth and activities of soil microorganisms that utilize plant-derived carbon as their primary energy source; and they report that subsequently enhanced activities of fungal and bacterial plant symbionts often lead to increased plant nutrient acquisition.

In a much more narrowly-focused study, Crookshanks *et al.* (1998) sprouted seeds of the small and fast-growing *Arabidopsis thaliana* plant on agar medium in Petri dishes and grew the resulting immature plants in controlled environment chambers maintained at atmospheric CO<sub>2</sub> concentrations of either 355 or 700 ppm. Visual assessments of root growth were made after emergence of the roots from the seeds, while microscopic investigations of root cell properties were also conducted. In pursuing this protocol, the scientists learned that the CO<sub>2</sub>-enriched plants directed a greater proportion of their newly-produced biomass into root, as opposed to shoot, growth. In addition, the young plants produced longer primary roots and more and longer lateral roots. These effects were found to be related to the CO<sub>2</sub>-induced stimulation of mitotic activity, accelerated cortical cell expansion, and increased cell wall plasticity.

In another unique study, Gouk *et al.* (1999) grew an orchid plantlet, Mokara Yellow, in plastic bags flushed with 350 and 10,000 ppm CO<sub>2</sub> for three months to study the effects of elevated CO<sub>2</sub> on this epiphytic CAM species. They determined that the super-elevated CO<sub>2</sub> of their experiment enhanced the total dry weight of the orchid plantlets by more than two-fold, while increasing the growth of existing roots and stimulating the induction of new roots from internodes located on the orchid stems. Total chlorophyll content was also increased by elevated CO<sub>2</sub> -- by 64% in young leaves and by 118% in young roots. This phenomenon permitted greater light harvesting during photosynthesis and likely led to the tissue starch contents of the CO<sub>2</sub>-enriched plantlets rising nearly 20-fold higher than those of the control-plantlets. In spite of this large CO<sub>2</sub>-induced accumulation of starch, however, no damage or disruption of chloroplasts was evident in the leaves and roots of the CO<sub>2</sub>-enriched plants.

A final question that has periodically intrigued researchers is whether plants take up carbon through their roots in addition to through their leaves. Although a definitive answer eludes us, various aspects of the issue have been described by Idso (1989), who we quote as follows.

"Although several investigators have claimed that plants should receive little direct benefit from dissolved CO<sub>2</sub> (Stolwijk *et al.*, 1957; Skok *et al.*, 1962; Splittstoesser, 1966), a number of experiments have produced significant increases in root growth (Erickson, 1946; Leonard and Pinckard, 1946; Geisler, 1963; Yorgalevitch and Janes, 1988), as well as yield itself (Kursanov *et al.*, 1951; Grinfeld, 1954; Nakayama and Bucks, 1980; Baron and Gorski, 1986), with CO<sub>2</sub>-enriched irrigation water. Early on, Misra (1951) suggested that this beneficent effect may be related to CO<sub>2</sub>-induced changes in soil nutrient availability; and this hypothesis may well be correct. Arteca *et al.* (1979), for example, have observed K, Ca and Mg to be better absorbed by potato roots when the concentration of CO<sub>2</sub> in the soil solution is increased; while Mauney and Hendrix (1988) found Zn and Mn to be better absorbed by cotton under such conditions, and Yurgalevitch and Janes (1988) found an enhancement of the absorption of Rb by tomato roots. In all cases, large increases in either total plant growth or ultimate yield accompanied the enhanced uptake of nutrients. Consequently, as it has been suggested that CO<sub>2</sub> concentration plays a major role in determining the porosity, plasticity and charge of cell membranes (Jackson and Coleman, 1959; Mitz, 1979), which could thereby alter ion uptake and organic acid production (Yorgalevitch and Janes, 1988), it is possible that some such suite of mechanisms may well be responsible for the plant productivity increases often observed to result from enhanced concentrations of CO<sub>2</sub> in the soil solution."

Although much is thus known about many aspects of root responses to atmospheric CO<sub>2</sub> enrichment, much remains to be learned. In this next section we review such responses for crops and then trees.

Additional information on this topic, including reviews on roots not discussed here, can be found at [http://www.co2science.org/subject/r/subject\\_r.php](http://www.co2science.org/subject/r/subject_r.php) under the heading Roots.

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#### 6.7.7.1. Crops

How do the roots of the crops we eat respond to atmospheric CO<sub>2</sub> enrichment? Unless the roots are the edible portion of the plant, we probably give the question little thought: "out of sight, out of mind," as the saying goes. But it is the *roots* that acquire the water and nutrients that sustain the plant; and so the question is of more than academic interest, providing a significant impetus for scientists to look beneath the surface of the subject *and the ground*. Hence, we here review what a few of them have found.

Hodge and Millard (1998) grew narrowleaf plantain (*Plantago lanceolata*) seedlings for a period of six weeks in controlled environment growth rooms maintained at atmospheric CO<sub>2</sub> concentrations of either 400 or 800 ppm. By the end of this period, the plants in the 800-ppm air exhibited increases in shoot and root dry matter production that were 159% and 180% greater, respectively, than the corresponding dry matter increases experienced by the plants growing in 400-ppm air, while the amount of plant carbon recovered from the potting medium (sand) was 3.2 times greater in the elevated-CO<sub>2</sub> treatment. Thus, these investigators found that the belowground growth stimulation provided by atmospheric CO<sub>2</sub> enrichment was greater than that experienced aboveground.

Wechsung *et al.* (1999) grew spring wheat (*Triticum aestivum*) in rows in a FACE study employing atmospheric CO<sub>2</sub> concentrations of 370 and 550 ppm and irrigation treatments that periodically replaced either 50% or 100% of prior potential evapotranspiration in an effort to determine the effects of elevated CO<sub>2</sub> and water stress on root growth. They found that elevated CO<sub>2</sub> increased *in-row* root dry weight by an average of 22% during the growing season under both the wet and dry irrigation regimes. In addition, during the vegetative growth phase, atmospheric CO<sub>2</sub> enrichment increased *inter-row* root dry weight by 70%, indicating that plants

grown in elevated CO<sub>2</sub> developed greater lateral root systems than plants grown at ambient CO<sub>2</sub>.

During the reproductive growth phase, elevated CO<sub>2</sub> stimulated the branching of lateral roots into inter-row areas, but only when water was limiting to growth. In addition, the CO<sub>2</sub>-enriched plants tended to display greater root dry weights at a given depth than did ambiently-grown plants. This study thus suggests that as the CO<sub>2</sub> content of the air continues to rise, spring wheat plants will likely develop larger and more extensively branching root systems that may help them to better cope with periods of reduced soil moisture availability.

In a comprehensive review of all prior FACE experiments conducted on agricultural crops, Kimball *et al.* (2002) determined that for a 300-ppm increase in atmospheric CO<sub>2</sub> concentration, the root biomass of wheat, ryegrass and rice experienced an average increase of 70% at ample water and nitrogen, 58% at low nitrogen and 34% at low water, while clover experienced a 38% increase at ample water and nitrogen, plus a 32% increase at low nitrogen. Outdoing all of the other crops was *cotton*, which exhibited a 96% increase in root biomass at ample water and nitrogen.

In a radically different type of study, Zhao *et al.* (2000) germinated pea (*Pisum sativum*) seeds and exposed the young plants to various atmospheric CO<sub>2</sub> concentrations in controlled environment chambers to determine if elevated CO<sub>2</sub> impacts root border cells, which are major contributors of root exudates in this and most other agronomic plants. They found that elevated CO<sub>2</sub> did indeed increase the production of root border cells in pea seedlings. In fact, in going from ambient air to air enriched to 3,000 and 6,000 ppm CO<sub>2</sub>, border-cell numbers increased by over 50% and 100%, respectively. Hence, as the CO<sub>2</sub> content of the air continues to rise, peas (and possibly many other crop plants) will likely produce greater numbers of root border cells, which should increase the amounts of root exudations occurring in their rhizospheres, which further suggests that associated soil microbial and fungal activities will be stimulated as a result of the increases in plant-derived carbon inputs that these organisms require to meet their energy needs. Last of all, this chain of events should make the soil environment even more favorable for plant growth and development in a high-CO<sub>2</sub> world of the future.

In concluding this brief review, we revisit the study of van Ginkel *et al.* (1996), who grew perennial ryegrass (*Lolium perenne*) plants from seed in two growth chambers for 71 days under continuous <sup>14</sup>CO<sub>2</sub>-labeling of the atmosphere at CO<sub>2</sub> concentrations of 350 and 700 ppm at two different soil nitrogen levels. At the conclusion of this part of the experiment, the plants were harvested and their roots dried, pulverized and mixed with soil in a number of one-liter pots that were placed within two wind tunnels in an open field, one of which had ambient air of 361 ppm CO<sub>2</sub> flowing through it, and one of which had air of 706 ppm CO<sub>2</sub> flowing through it. Several of the containers were then seeded with more *Lolium perenne*, others were similarly seeded the following year, and still others were kept bare for two years. Then, at the ends of the first and second years, the different degrees of decomposition of the *original* plant roots were assessed.



It was determined, first of all, that shoot and root growth were enhanced by 13 and 92%, respectively, by the extra CO<sub>2</sub> in the initial 71-day portion of the experiment, once again demonstrating the significantly greater benefits that are often conferred upon plant roots by atmospheric CO<sub>2</sub> enrichment. Secondly, it was found that the decomposition of the high-CO<sub>2</sub>-grown roots in the high-CO<sub>2</sub> wind tunnel was 19% lower than that of the low-CO<sub>2</sub>-grown roots in the low-CO<sub>2</sub> wind tunnel at the end of the first year, and that it was 14% lower at the end of the second year *in the low-nitrogen-grown plants* but equivalent in the high-nitrogen-grown plants. It was also determined that the presence of living roots reduced the decomposition rate of dead roots below the dead-root-only decomposition rate observed in the bare soil treatment.

Based on these findings, van Ginkel *et al.* conclude that "the combination of higher root yields at elevated CO<sub>2</sub> combined with a decrease in root decomposition will lead to a longer residence time of C in the soil and probably to a higher C storage."

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/r/rootscrops.php>.

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### 6.7.7.2. Trees

Trees figure prominently in political and economic schemes designed to promote the biospheric sequestration of carbon as a means for slowing the rate of rise of the air's CO<sub>2</sub> content and thereby reducing the supposed severity of CO<sub>2</sub>-induced global warming. Nature also employs trees for this purpose, but without any of the burdensome strings that come attached to the

plans of man. In *both* instances, however, it is useful to learn whatever we can about the potential for the world's forests to perform this important function.

In this regard, one can readily see and measure the carbon that goes into the aboveground components of forests. But what about the underground components? And how does the ongoing rise in the atmosphere's CO<sub>2</sub> concentration, which is the supposed cause of the pseudo-problem, contribute to its pseudo-resolution? In this brief review we summarize the findings of some recent studies of *trees* that address this question.

Janssens *et al.* (1998) grew three-year-old Scots pine seedlings for a period of six months in open-top chambers maintained at ambient and 700 ppm atmospheric CO<sub>2</sub>, finding that the extra CO<sub>2</sub> increased total root length by 122% and total root dry mass by 135%. In a similar study that employed close to the same degree of enhancement of the air's CO<sub>2</sub> content, Pritchard *et al.* (2001a) grew idealized ecosystems representative of regenerating longleaf pine forests of the southeastern USA for a period of 18 months in large soil bins located within open-top chambers. The aboveground parts of these seedlings only experienced a growth enhancement of 20%. The *root* biomass of the trees, however, was increased by *more than three times as much* (62%).

Working with FACE technology, Pritchard *et al.* (2001b) studied 14-year-old loblolly pine trees after a year of exposure to an extra 200 ppm of CO<sub>2</sub>, finding that total standing root length and root numbers were 16 and 34% greater, respectively, in the CO<sub>2</sub>-enriched plots than in the ambient-air plots. In addition, the elevated CO<sub>2</sub> increased the diameter of living and dead roots by 8 and 6%, respectively, while annual root production was found to be 26% greater in the CO<sub>2</sub>-enriched plots. For the degree of CO<sub>2</sub> enrichment employed in the prior two studies, this latter enhancement corresponds to a root biomass increase of approximately 45%.

In an open-top chamber study of a model ecosystem composed of a mixture of spruce and beech seedlings, Wiemken *et al.* (2001) investigated the effects of a 200 ppm increase in the air's CO<sub>2</sub> concentration that prevailed for a period of four years. On nutrient-poor soils, the extra CO<sub>2</sub> led to a 30% increase in fine-root biomass, while on nutrient-rich soils it led to a 75% increase. As before, these numbers correspond to increases of about 52% and 130%, respectively, for atmospheric CO<sub>2</sub> enhancements on the order of those employed by Janssens *et al.* (1998) and Pritchard *et al.* (2001a).

Another interesting aspect of the Wiemken *et al.* study was their finding that the extra CO<sub>2</sub> increased the amount of symbiotic fungal biomass associated with the trees' fine roots by 31% on nutrient-poor soils and by 100% on nutrient-rich soils, which for the degree of atmospheric CO<sub>2</sub> enrichment used in the studies of Janssens *et al.* (1998) and Pritchard *et al.* (2001a) translate into increases of about 52% and 175%, respectively.

Berntsen and Bazzaz (1998) removed intact chunks of soil from the Hardwood-White Pine-Hemlock forest region of New England and placed them in plastic containers within controlled environment glasshouses maintained at either 375 or 700 ppm CO<sub>2</sub> for a period of two years in

order to study the effects of elevated CO<sub>2</sub> on the regeneration of plants from seeds and rhizomes present in the soil. At the conclusion of the study, total mesocosm plant biomass (more than 95% of which was supplied by yellow and white birch tree seedlings) was found to be 31% higher in the elevated CO<sub>2</sub> treatment than in ambient air, with a mean enhancement of 23% aboveground and 62% belowground. The extra CO<sub>2</sub> also increased the mycorrhizal colonization of root tips by 45% in white birch and 71% in yellow birch; and the CO<sub>2</sub>-enriched yellow birch seedlings exhibited 322% greater root length and 305% more root surface area than did the yellow birch seedlings growing in ambient air.

Kubiske *et al.* (1998) grew cuttings of four quaking aspen genotypes in open-top chambers for five months at atmospheric CO<sub>2</sub> concentrations of either 380 or 720 ppm and low or high soil nitrogen concentrations. They found, surprisingly, that the cuttings grown in elevated CO<sub>2</sub> displayed no discernible increases in aboveground growth. However, the extra CO<sub>2</sub> significantly increased fine-root length and root turnover rates at high soil nitrogen by increasing fine-root production, which would logically be expected to produce benefits (not the least of which would be a larger belowground water- and nutrient-gathering system) that would eventually lead to enhanced aboveground growth as well. That this reasoning is indeed correct may be verified by perusing the many positive aboveground growth responses of quaking aspen trees to atmospheric CO<sub>2</sub> enrichment that are listed in the biomass portion of the Plant Growth Data section of our website (see *Populus tremuloides* Michx.).

Expanding on this study, Pregitzer *et al.* (2000) grew six quaking aspen genotypes for 2.5 growing seasons in open-top chambers maintained at atmospheric CO<sub>2</sub> concentrations of 350 and 700 ppm with both adequate and inadequate supplies of soil nitrogen. This work demonstrated that the trees exposed to elevated CO<sub>2</sub> developed thicker and longer roots than the trees growing in ambient air, and that the fine-root biomass of the CO<sub>2</sub>-enriched trees was enhanced by 17% in the nitrogen-poor soils and by 65% in the nitrogen-rich soils.

Yet another study of quaking aspen conducted by King *et al.* (2001) demonstrated that trees exposed to an atmospheric CO<sub>2</sub> concentration 560 ppm in a FACE experiment produced 133% more fine-root biomass than trees grown in ambient air of 360 ppm, which roughly equates to 233% more fine-root biomass for the degree of CO<sub>2</sub> enrichment employed in the prior study of Pregitzer *et al.* And when simultaneously exposed to air of 1.5 times the normal ozone concentration, the degree of fine-root biomass stimulation produced by the extra CO<sub>2</sub> was still as great as 66%, or roughly 115% when extrapolated to the greater CO<sub>2</sub> enrichment employed by Pregitzer *et al.*

In a final quaking aspen study, King *et al.* (1999) grew four clones at two different temperature regimes (separated by 5°C) and two levels of soil nitrogen (N) availability (high and low) for 98 days, while measuring photosynthesis, growth, biomass allocation, and root production and mortality. They found that the higher of the two temperature regimes increased rates of photosynthesis by 65% and rates of whole-plant growth by 37%, while it simultaneously enhanced root production and turnover. It was thus their conclusion that "trembling aspen has the potential for substantially greater growth and root turnover under conditions of warmer

soil at sites of both high and low N-availability" and that "an immediate consequence of this will be greater inputs of C and nutrients to forest soils."

In light of these several findings pertaining to quaking aspen trees, it is evident that increases in atmospheric CO<sub>2</sub> concentration, air temperature and soil nitrogen content all enhance their belowground growth, which positively impacts their aboveground growth. And it is important to note that all of these environmental changes have been imputed to occur as a consequence of the burning of fossil fuels.

Turning our attention to other deciduous trees, we focus next on the study of Gleadow *et al.* (1998), who grew eucalyptus seedlings for six months in glasshouses maintained at atmospheric CO<sub>2</sub> concentrations of either 400 or 800 ppm, fertilizing them twice daily with low or high nitrogen solutions. The elevated CO<sub>2</sub> of their experiment increased total plant biomass by 98 and 134% relative to plants grown at ambient CO<sub>2</sub> in the high and low nitrogen treatments, respectively. In addition, in the low nitrogen treatment, elevated CO<sub>2</sub> stimulated greater root growth, as indicated by a 33% higher root:shoot ratio.

In a more complex study, Day *et al.* (1996) studied the effects of elevated CO<sub>2</sub> on fine-root production in open-top chambers erected over a regenerating oak-palmetto scrub ecosystem in Florida, USA, determining that a 350-ppm increase in the atmosphere's CO<sub>2</sub> concentration increased fine-root length densities by 63% while enhancing the distribution of fine roots at both the soil surface (0-12 cm) and at a depth of 50-60 cm. These findings suggest that the ongoing rise in the atmosphere's CO<sub>2</sub> concentration will likely increase the distribution of fine roots near the soil surface, where the greatest concentrations of nutrients are located, and at a depth that coincides with the upper level of the site's water table, both of which phenomena should increase the trees' ability to acquire the nutrients and water they will need to support CO<sub>2</sub>-enhanced biomass production in the years and decades ahead.

In another study that employed CO<sub>2</sub>, temperature and nitrogen as treatments, Uselman *et al.* (2000) grew seedlings of the nitrogen-fixing black locust tree for 100 days in controlled environments maintained at atmospheric CO<sub>2</sub> concentrations of 350 and 700 ppm and air temperatures of 26°C (ambient) and 30°C, with either some or no additional nitrogen fertilization, finding that the extra CO<sub>2</sub> increased total seedling biomass by 14%, that the elevated temperature increased it by 55%, and that nitrogen fertilization increased it by 157%. With respect to root exudation, a similar pattern was seen. Plants grown in elevated CO<sub>2</sub> exuded 20% more organic carbon compounds than plants grown in ambient air, while elevated temperature and fertilization increased root exudation by 71 and 55%, respectively. Hence, as the air's CO<sub>2</sub> content continues to rise, black locust trees will likely exhibit enhanced rates of biomass production and exudation of dissolved organic compounds from their roots. Moreover, if air temperature also rises, even by as much as 4°C, its positive effect on biomass production and root exudation will likely be even greater than that resulting from the increasing atmospheric CO<sub>2</sub> concentration; and the same would appear to hold true for anthropogenic nitrogen deposition, reinforcing what was learned about the impacts of these three environmental factors on the growth of quaking aspen trees.

In a somewhat different type of study, McDowell *et al.* (1999) grew five-month-old seedlings of western hemlock in root boxes, subjecting them for several hours to various root-space CO<sub>2</sub> concentrations, ranging from approximately 90 to 7000 ppm, in order to determine the effect of soil CO<sub>2</sub> concentration on growth, maintenance and total root respiration. Although they could detect no effect of atmospheric CO<sub>2</sub> enrichment on growth respiration, it significantly impacted maintenance and total respiration rates. At a soil CO<sub>2</sub> concentration of 1585 ppm, for example, total and maintenance respiration rates were 55 and 60% lower, respectively, than they were at a soil CO<sub>2</sub> concentration of 395 ppm. In fact, the impact of elevated soil CO<sub>2</sub> on maintenance respiration (which comprised 85% of the total respiration in this study) was so strong that it exhibited an exponential decline of about 37% for every doubling of the soil CO<sub>2</sub> concentration.

In light of these several experimental findings, it can confidently be concluded that the ongoing rise in the air's CO<sub>2</sub> content, together with possible concurrent increases in air temperature and nitrogen deposition, will likely help earth's woody plants to become ever more robust and productive as atmospheric CO<sub>2</sub> concentrations rise higher and higher.

This brief sampling of the scientific literature suggests that the ongoing rise in the air's CO<sub>2</sub> content bodes well for the growth of earth's coniferous forests and their ability to sequester carbon. These consequences have great virtue in and of themselves and are worthy of being pursued on the basis of their own intrinsic value; and as they comprise a potentially powerful negative feedback on CO<sub>2</sub>-induced global warming, there is yet a *third* reason for lauding their existence.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/r/rootsconifers.php> and <http://www.co2science.org/subject/r/rootsdeciduous.php>.

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### 6.7.8. Seeds

Additional information on this topic, including reviews on seeds not discussed here, can be found at [http://www.co2science.org/subject/s/subject\\_s.php](http://www.co2science.org/subject/s/subject_s.php) under the heading Seeds.

### 6.7.8.1. Crops

When dealing with agricultural commodities such as grain crops, seeds comprise the yield; and in such cases, the biomass of one is the biomass of the other. Hence, when looking for effects of elevated CO<sub>2</sub> on the *seeds* of such crops, one is naturally interested in something more than just their final biomass; and in this brief synopsis of pertinent papers we have reviewed, we consider a number of the *sources* of biomass production, as well as seed properties that go *beyond biomass*.

In a greenhouse study of the various *components* of seed biomass production, Palta and Ludwig (2000) grew narrow-leafed lupin in pots filled with soil within Mylar-film tunnels maintained at either 355 or 700 ppm CO<sub>2</sub>. They found that the extra CO<sub>2</sub> increased (1) the final number of pods and (2) the number of pods that filled large seeds, while it (3) reduced to zero the number of pods that had small seeds, (4) reduced the number of pods with unfilled seeds from 16 to 1 pod per plant, and increased (5) pod set and (6) dry matter accumulation on the developing branches. These several CO<sub>2</sub>-induced improvements to key physiological processes resulted in 47 to 56% increases in dry matter per plant, which led to increases of 44 to 66% in seed yield per plant.

Sanhewe *et al.* (1996) grew winter wheat in polyethylene tunnels maintained at atmospheric CO<sub>2</sub> concentrations of 380 and 680 ppm from the time of seed germination to the time of plant maturity, while maintaining a temperature gradient of approximately 4°C in each tunnel. In addition to the elevated CO<sub>2</sub> increasing seed yield per unit area, they found it also increased seed weight, but not seed survival or germination. Increasing air temperature, on the other hand, increased seed longevity across the entire range of temperatures investigated (14 to 19°C).

Thomas *et al.* (2003) grew soybean plants to maturity in sunlit controlled-environment chambers under sinusoidally-varying day/night-max/min temperatures of 28/18, 32/22, 36/26, 40/30 and 44/34°C and two levels of atmospheric CO<sub>2</sub> concentration (350 and 700 ppm). They determined, in their words, that the effect of temperature on seed composition and gene expression was "pronounced," but that "there was no effect of CO<sub>2</sub>." In this regard, however, they note that "Heagle *et al.* (1998) observed a positive significant effect of CO<sub>2</sub> enrichment on soybean seed oil and oleic acid concentration," the latter of which parameters Thomas *et al.* found to increase with rising temperature all the way from 28/18 to 44/34°C. They also found that "32/22°C is optimum for producing the highest oil concentration in soybean seed," and that "the degree of fatty acid saturation in soybean oil was significantly increased by increasing temperature." In addition, they determined that crude protein concentration increased with temperature to 40/30°C.

In commenting on these findings, Thomas *et al.* note that "the intrinsic value of soybean seed is in its supply of essential fatty acids and amino acids in the oil and protein, respectively." This being the case, the temperature-driven changes they identified in these parameters, as well as the CO<sub>2</sub> effect observed by Heagle *et al.*, bode well for the future production of this important crop and its value to society in a CO<sub>2</sub>-enriched and warming world. They do note, however,

that "temperatures during the soybean-growing season in the southern USA are at, or slightly higher than, 32/22°C," and that warming could negatively impact the soybean oil industry in this region. For the world as a whole, however, warming would be a positive development for soybean production; while in the southern United States, shifts in planting zones could readily accommodate changing weather patterns associated with this phenomenon.

In another soybean study, Ziska *et al.* (2001) grew one modern and eight ancestral genotypes in glasshouses maintained at atmospheric CO<sub>2</sub> concentrations of 400 and 710 ppm, finding that the extra CO<sub>2</sub> increased photosynthetic rates by an average of 75%. This enhancement in photosynthetic sugar production led to increases in seed yield that averaged 40% for all cultivars, except for one ancestral variety that exhibited an 80% increase in seed yield. Hence, if plant breeders were to utilize the highly CO<sub>2</sub>-responsive ancestral cultivar identified in this study in their breeding programs, it is possible that soybean seed yields - and all of the other good things that go with it - could be made to rise even faster and higher in the days and years ahead.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/s/seedscrops.php>.

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### 6.7.8.2. Grasslands

We begin this section review of elevated atmospheric CO<sub>2</sub> effects on seed production -- as well as the subsequent phenomena they trigger -- with the study of Steinger *et al.* (2000), who collected seeds from *Bromus erectus* plants that had been grown at atmospheric CO<sub>2</sub> concentrations of 360 and 650 ppm, and who germinated some of both groups of seeds under



those same two sets of conditions. In the first part of their study, they found that the elevated CO<sub>2</sub> treatment (1) increased individual seed mass by about 9% and (2) increased seed carbon-to-nitrogen ratio by almost 10%. However, they also learned that these changes in seed properties had little impact on subsequent seedling growth. In fact, when the seeds produced by ambient or CO<sub>2</sub>-enriched plants were germinated and grown in ambient air, there was no significant size difference between the two groups of resultant seedlings after a period of 19 days. Likewise, when the seeds produced from ambient or CO<sub>2</sub>-enriched plants were germinated and grown in the high CO<sub>2</sub> treatment, there was also no significant difference between the sizes of the seedlings derived from the two groups of seeds. However, the CO<sub>2</sub>-enriched seedlings produced from both groups of seeds were almost 20% larger than the seedlings produced from *both* groups of seeds grown in ambient air, demonstrating that the direct effects of elevated atmospheric CO<sub>2</sub> concentration on seedling growth and development were more important than the differences in seed characteristics produced by the elevated atmospheric CO<sub>2</sub> concentration in which their parent plants grew.

In another study conducted about the same time, Edwards *et al.* (2001) utilized a FACE experiment where daytime atmospheric CO<sub>2</sub> concentrations above a sheep-grazed pasture in New Zealand were increased by 115 ppm to study the effects of elevated CO<sub>2</sub> on seed production, seedling recruitment and species compositional changes. In the two years of their study, the extra daytime CO<sub>2</sub> increased seed production and dispersal in seven of the eight most abundant species, including the grasses *Anthoxanthum odoratum*, *Lolium perenne* and *Poa pratensis*, the legumes *Trifolium repens* and *T. subterranean*, and the herbs *Hypochaeris radicata* and *Leontodon saxatilis*. In some of these plants, elevated CO<sub>2</sub> increased the number of seeds per reproductive structure, while all of them exhibited CO<sub>2</sub>-induced increases in the number of reproductive structures per unit of ground area. In addition, they determined that the CO<sub>2</sub>-induced increases in seed production contributed in a major way to the increase in the numbers of species found within the CO<sub>2</sub>-enriched plots.

In a five-year study of a nutrient-poor calcareous grassland in Switzerland, Thurig *et al.* (2003) used screen-aided CO<sub>2</sub> control (SACC) technology (Leadley *et al.*, 1997) to enrich the air over half of their experimental plots with an extra 300 ppm of CO<sub>2</sub>, finding that "the effect of elevated CO<sub>2</sub> on the number of flowering shoots (+24%) and seeds (+29%) at the community level was similar to above ground biomass response." In terms of species functional groups, there was a 42% increase in the mean seed number of graminoids and a 33% increase in the mean seed number of forbs, but no change in legume seed numbers. In most species, mean seed weight also tended to be greater in plants grown in CO<sub>2</sub>-enriched air (+12%); and Thurig *et al.* say it is known from many studies that heavier seeds result in seedlings that "are more robust than seedlings from lighter seeds (Baskin and Baskin, 1998)."

Rounding out the papers we have reviewed on this subject, Wang and Griffin (2003) grew dioecious white cockle plants from seed to maturity in sand-filled pots maintained at optimum moisture and fertility conditions in environmentally-controlled growth chambers in which the air was continuously maintained at CO<sub>2</sub> concentrations of either 365 or 730 ppm. In response to this doubling of the air's CO<sub>2</sub> content, the vegetative mass of both male and female plants

rose by approximately 39%. Reproductive mass, on the other hand, rose by 82% in male plants and by 97% in females. In the female plants, this feat was accomplished, in part, by increases of 36% and 44% in the number and mass of seeds per plant, and by a 15% increase in the mass of individual seeds, in harmony with the findings of Jablonski *et al.* (2002), which they derived from a meta-analysis of the results of 159 CO<sub>2</sub> enrichment experiments conducted on 79 species of agricultural and wild plants. Hence, because dioecious plants comprise nearly half of all angiosperm families, we may expect to see a greater proportion of plant biomass allocated to reproduction in a high-CO<sub>2</sub> world of the future, which ultimate result should bode well indeed for the biodiversity of earth's many ecosystems.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/s/seedsgrasslands.php>.

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### 6.7.8.3. Trees

How does enriching the air with carbon dioxide impact the reproductive capacity of trees? LaDeau and Clark (2001) addressed this question in a major way when they determined the reproductive response of loblolly pine trees to atmospheric CO<sub>2</sub> enrichment at Duke Forest in the Piedmont region of North Carolina, USA, where in August of 1996 three 30-m-diameter FACE rings began to enrich the air around the 13-year-old trees they encircled to 200 ppm above the atmosphere's normal background concentration, while three other FACE rings served as control plots. Because the trees were not mature at the start of the experiment they did not produce any cones until a few rare ones appeared in 1998. By the fall of 1999, however, the

two scientists found that, compared to the trees growing in ambient air, the CO<sub>2</sub>-enriched trees were twice as likely to be reproductively mature and produced three times more cones per tree. Similarly, the trees growing in the CO<sub>2</sub>-enriched air produced 2.4 times more cones in the fall of 2000; and from August 1999 through July 2000, they collected three times as many seeds in the CO<sub>2</sub>-fertilized FACE rings as in the control rings.

Also working on this aspect of the Duke Forest FACE study were Hussain *et al.* (2001), who report that (1) seeds collected from the CO<sub>2</sub>-enriched trees were 91% heavier than those collected from the trees growing in ambient air, (2) the CO<sub>2</sub>-enriched seeds had a lipid content that was 265% greater than that of the seeds produced on the ambient-treatment trees, (3) the germination success for seeds developed under atmospheric CO<sub>2</sub> enrichment was more than three times greater than that observed for control seeds developed at ambient CO<sub>2</sub>, regardless of germination CO<sub>2</sub> concentration, (4) seeds from the CO<sub>2</sub>-enriched trees germinated approximately five days earlier than their ambiently-produced counterparts, again regardless of germination CO<sub>2</sub> concentration, and (5) seedlings developing from seeds collected from CO<sub>2</sub>-enriched trees displayed significantly greater root lengths and needle numbers than seedlings developing from trees exposed to ambient air, also regardless of growth CO<sub>2</sub> concentration.

What are the implications of these findings? The propensity for elevated levels of atmospheric CO<sub>2</sub> to hasten the production of more plentiful seeds on the trees of this valuable timber species bodes well for naturally-regenerated loblolly pine stands of the southeastern United States, where LaDeau and Clark report these trees "are profoundly seed-limited for at least 25 years." Hence, as the air's CO<sub>2</sub> content continues to climb, they conclude that "this period of seed limitation may be reduced," which is good news for this highly-prized tree. In addition, the observations of Hussain *et al.* suggest that loblolly pine trees in a CO<sub>2</sub>-enriched world of the future will likely display significant increases in their photosynthetic rates. Enhanced carbohydrate supplies resulting from this phenomenon will likely be used to increase seed weight and lipid content. Such seeds should consequently exhibit significant increases in germination success, and their enhanced lipid supplies will likely lead to greater root lengths and needle numbers in developing seedlings. Consequently, when CO<sub>2</sub>-enriched loblolly pine seedlings become photosynthetically-active, they will likely photosynthesize and produce biomass at greater rates than those exhibited by seedlings growing under current ambient CO<sub>2</sub> concentrations.

Another major study of the reproductive responses of trees to elevated levels of atmospheric CO<sub>2</sub> was conducted at the Kennedy Space Center, Florida, USA, where in 1996 three species of scrub-oak (*Quercus myrtifolia*, *Q. chapmanii*, and *Q. geminata*) were enclosed within sixteen open-top chambers, half of which were maintained at 379 ppm CO<sub>2</sub> and half at 704 ppm. Five years later -- in August, September and October of 2001 -- Stiling *et al.* (2004) counted the numbers of acorns on randomly selected twigs of each species, while in November of that year they counted the numbers of fallen acorns of each species within equal-size quadrates of ground area, additionally evaluating mean acorn weight, acorn germination rate, and degree of acorn infestation by weevils. So what did they find?

Acorn germination rate and degree of predation by weevils were unaffected by elevated CO<sub>2</sub>, while acorn size was enhanced by a small amount: 3.6% for *Q. myrtifolia*, 7.0% for *Q. chapmanii*, and 7.7% for *Q. geminata*. Acorn number responses, on the other hand, were enormous, but for only two of the three species, as *Q. geminata* did not register any CO<sub>2</sub>-induced increase in reproductive output, in harmony with its unresponsive overall growth rate. For *Q. myrtifolia*, however, Stiling *et al.* report "there were four times as many acorns per 100 twigs in elevated CO<sub>2</sub> as in ambient CO<sub>2</sub> and for *Q. chapmanii* the increase was over threefold." On the ground, the enhancement was greater still, with the researchers reporting that "the number of *Q. myrtifolia* acorns per meter squared in elevated CO<sub>2</sub> was over seven times greater than in ambient CO<sub>2</sub> and for *Q. chapmanii*, the increase was nearly sixfold."

Stiling *et al.* say that these results lead them to believe "there will be large increases in seedling production in scrub-oak forests in an atmosphere of elevated CO<sub>2</sub>," noting that "this is important because many forest systems are 'recruitment-limited' (Ribbens *et al.*, 1994; Hubbell *et al.*, 1999)," which conclusion echoes that of LaDeau and Clark with respect to loblolly pines. If other trees behave similarly, it would appear that the rising CO<sub>2</sub> content of earth's atmosphere will be a boon indeed to the regenerative prowess of the planet's forests. More research results from other tree species are thus anxiously awaited.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/s/seedstrees.php>.

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### 6.7.9. Tannins

Condensed tannins are naturally-occurring secondary carbon compounds produced in the leaves of a number of different plants that often act to deter herbivorous insects. How do condensed tannin concentrations in the leaves and roots trees respond to atmospheric CO<sub>2</sub> enrichment? We here briefly summarize the findings of several studies for aspen, birch and oak trees.

Additional information on this topic, including reviews on tannins not discussed here, can be found at [http://www.co2science.org/subject/t/subject\\_t.php](http://www.co2science.org/subject/t/subject_t.php) under the heading Tannins.

#### 6.7.9.1. Aspen Trees

In New Zealand, the Legume Lotus is a good source of condensed tannins; and scientists with the country's *AgResearch Grasslands* institute have additionally determined that sheep and cattle feeding on forage that contains this plant may see their methane emissions reduced by as much as 16%.

This latter finding is of special importance to New Zealanders, because the methane expelled in the breath of cattle and sheep - which is a by-product of the fermentation of feed in the rumen of these animals - accounts for close to 90% of the country's methane emissions. Consequently, a significant reduction in such a large national source of one of the atmosphere's most potent greenhouse gases would go a long way towards helping the country reduce its emissions of climate-altering substances, which would be, according to the press release that described this development, "very welcome." The press release also states that tannins "have a variety of other animal related benefits, such as improved milk yield, increased liveweight gain, decreased internal parasite burden and reduced occurrence of bloat, dags and fly strike."

In this regard, it is important to note that in addition to sheep and cattle, *ruminants*, as they are called, comprise a great group of animals (four-footed, hooved, even-toed, cud-chewing mammals that have a stomach consisting of four divisions or chambers) that includes antelope, bison, buffalo, camel, deer, giraffe, goat, llama, etc., and that these animals eat a number of other types of plants, which may also experience increases in leaf tannin production as the air's CO<sub>2</sub> content rises. In this Summary, therefore, we *begin* an investigation of this subject as it applies to aspen (*Populus tremuloides*) trees.

King *et al.* (2001) grew aspen seedlings for five months in open-top chambers maintained at atmospheric CO<sub>2</sub> concentrations of either 350 or 700 ppm. At the end of this period, naturally-senesced leaf *litter* was collected and analyzed; and it was found that the elevated CO<sub>2</sub> of this particular study had *no* effect on leaf litter tannin concentration.

A substantially different result was obtained in an earlier study of aspen *leaves* that was conducted by McDonald *et al.* (1999), who grew aspen seedlings in controlled environment greenhouses that were maintained at either ambient (387 ppm) or elevated (696 ppm) CO<sub>2</sub> concentrations under conditions of either low or high light availability (half and full sunlight,

respectively) for 31 days after the mean date of bud break. In this case it was determined that under low light conditions, the CO<sub>2</sub>-enriched seedlings exhibited an increase of approximately 15% in leaf condensed tannin concentration, while under high light conditions the CO<sub>2</sub>-induced increase in leaf condensed tannin concentration was a whopping 175%.

In a much more complex study than either of the two preceding ones, Agrell *et al.* (2005) examined the effects of ambient and elevated concentrations of atmospheric CO<sub>2</sub> (360 ppm and 560 ppm, respectively) and O<sub>3</sub> (35-60 ppb and 52-90 ppb, respectively) on the foliar chemistry of more mature aspen trees of two different genotypes (216 and 259) growing out-of-doors at the Aspen Free Air CO<sub>2</sub> Enrichment (FACE) facility near Rhinelander, Wisconsin, USA, as well as the impacts of these effects on the host plant preferences of forest tent caterpillar larvae.

In reporting the results of the study, Agrell *et al.* say that "the only chemical component showing a somewhat consistent covariation with larval preferences was condensed tannins," noting that "the tree becoming relatively less preferred as a result of CO<sub>2</sub> or O<sub>3</sub> treatment was in general also the one for which average levels of condensed tannins were most positively (or least negatively) affected by that treatment." In this regard, it is of interest to note that the mean condensed tannin concentrations of the aspen 216 and 259 genotypes were 25% and 57% higher, respectively, under the elevated CO<sub>2</sub> and O<sub>3</sub> combination treatment compared to the ambient CO<sub>2</sub> and O<sub>3</sub> combination treatment.

In light of these findings, it is logical to presume that as atmospheric concentrations of CO<sub>2</sub> and O<sub>3</sub> continue to rise, the increase in condensed tannin concentration likely to occur in the foliage of aspen trees should lead to their leaves becoming less preferred for consumption by the dreaded forest tent caterpillar, which according to Agrell *et al.* is "an eruptive generalist defoliator in North American hardwood forests, causing extensive damage during outbreak years (Fitzgerald, 1995)." Also, because the amount of methane expelled in the breath of ruminants is an inverse function of the condensed tannin concentration of the foliage they consume, the increased aspen foliage tannin concentrations likely to exist in a high-CO<sub>2</sub> world of the future should result in less methane being released to the atmosphere via ruminants browsing on aspen foliage, which phenomenon should act to decrease the impetus for methane-induced global warming.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/t/tanninsaspen.php>.

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#### 6.7.9.2. Birch Trees

How do condensed tannin concentrations in the leaves and roots of paper birch (*Betula papyrifera* Marsh.) and silver birch (*Betula pendula* Roth) trees respond to atmospheric CO<sub>2</sub> enrichment with and without concomitant increases in atmospheric temperature and ozone concentrations? We here briefly summarize the findings of several studies that have broached one or more parts of this question.

McDonald *et al.* (1999) grew paper birch seedlings in controlled environment greenhouses that were maintained at either ambient (387 ppm) or elevated (696 ppm) CO<sub>2</sub> concentrations under conditions of either low or high light availability (half and full sunlight, respectively) for 31 days after the mean date of bud break. In doing so, they determined that under low light conditions the CO<sub>2</sub>-enriched seedlings exhibited an increase of approximately 15% in leaf condensed tannin concentration, while under high light conditions the CO<sub>2</sub>-induced tannin increase was a whopping 175%.

Peltonen *et al.* (2005) studied the impacts of doubled atmospheric CO<sub>2</sub> and O<sub>3</sub> concentrations on the accumulation of 27 phenolic compounds, including soluble condensed tannins, in the leaves of two European silver birch clones in seven-year-old soil-grown trees that were exposed in open-top chambers for three growing seasons to ambient and twice-ambient atmospheric CO<sub>2</sub> and O<sub>3</sub> concentrations singly and in combination. This work, which was carried out in central Finland, revealed that elevated CO<sub>2</sub> increased the concentration of soluble condensed tannins in the leaves of the trees by 19%. In addition, they found that the elevated CO<sub>2</sub> protected the leaves from elevated O<sub>3</sub> because, as they describe it, "all the O<sub>3</sub>-derived effects on the leaf phenolics and traits were prevented by elevated CO<sub>2</sub>."

Kuokkanen *et al.* (2003) grew two-year-old silver birch seedlings in ambient air of 350 ppm CO<sub>2</sub> or air enriched to a CO<sub>2</sub> concentration of 700 ppm under conditions of either ambient temperature or ambient temperature plus 3°C for one full growing season in the field in closed-top chambers at the Mekrijärvi Research Station of the University of Joensuu in eastern Finland. Then, during the middle of the summer, when carbon-based secondary compounds of birch leaves are fairly stable, they picked several leaves from each tree and determined their condensed tannin concentrations, along with the concentrations of a number of other physiologically-important substances. This work revealed that the concentration of total phenolics, condensed tannins and their derivatives significantly increased in the leaves produced in the CO<sub>2</sub>-enriched air, as has also been observed by Lavola and Julkunen-Titto (1994), Williams *et al.* (1994), Kinney *et al.* (1997), Bezemer and Jones (1998) and Kuokkanen *et al.* (2001). In fact, the extra 350 ppm of CO<sub>2</sub> nearly *tripled* condensed tannin concentrations in

the ambient-temperature air, while it increased their concentrations in the elevated-temperature air by a factor *in excess of 3.5*.

In a study of roots, Parsons *et al.* (2003) grew two-year-old paper birch saplings in well-watered and fertilized 16-L pots from early May until late August in glasshouse rooms maintained at either 400 or 700 ppm CO<sub>2</sub>. This procedure revealed that the concentration of condensed tannins in the fine roots of the saplings was increased by 27% in the CO<sub>2</sub>-enriched treatment; and in regard to this finding, the researchers say "the higher condensed tannin concentrations that were present in the birch fine roots may offer these tissues greater protection against soil-borne pathogens and herbivores."

Parsons *et al.* (2004) collected leaf litter samples from early September to mid-October beneath paper birch trees growing in ambient and CO<sub>2</sub>-enriched (to 200 ppm above ambient) FACE plots in northern Wisconsin, USA, which were also maintained under ambient and O<sub>3</sub>-enriched (to 19 ppb above ambient) conditions, after which the leaf mass produced in each treatment was determined, sub-samples of the leaves were assessed for a number of chemical constituents (including nitrogen, which hastens leaf decay, and condensed tannins, which retard decay), and the remaining leaves were placed in 1-mm-aperture litterbags made of fiberglass cloth and left to decay upon the ground for the next twelve months under the same atmospheric conditions in which they were produced. Then, at the conclusion of the one-year litter-exposure period, the mass of remaining litter was measured and the time required to achieve 95% mass loss determined.

In following this protocol, the researchers learned that under ambient O<sub>3</sub> conditions, the *nitrogen* concentrations of the leaves in the CO<sub>2</sub>-enriched plots at the time of litterfall were 31% *less* than those of the leaves in the ambient-CO<sub>2</sub> plots, while condensed tannin concentrations were 64% *greater* in the CO<sub>2</sub>-enriched plots. Similarly, under the O<sub>3</sub>-enriched conditions, leaf nitrogen concentrations were a nearly-identical 32% less, while condensed tannins concentrations a much-larger 99% greater.

These observations suggest that leaf decay rates in the CO<sub>2</sub>-enriched plots should be lower than those in the ambient-CO<sub>2</sub> plots; and the mass-loss rates determined at the end of the one-year exposure period bore out this expectation, with Parsons *et al.* reporting that "for control litter, 5% of mass remained after 3.6 years, while CO<sub>2</sub>-enriched litter took ~4.5 years to turn over 95% of its mass." Hence, it could well take 25% more time (4.5 years / 3.6 years) to lose an equivalent percentage of paper birch leaf litter from CO<sub>2</sub>-enriched forests, independent of the air's O<sub>3</sub> concentration. And combining this fact with the facts that the CO<sub>2</sub>-enriched trees, in the words of the researchers, "attained greater size, and a greater degree of canopy closure, and contributed more litterfall to the development of [the] forest floor than did trees in the control rings," it is clear that the ongoing rise in the atmosphere's CO<sub>2</sub> concentration should greatly augment the sequestration of carbon by paper birch tree stands as the air's CO<sub>2</sub> content climbs ever higher.



In another study conducted at the Wisconsin FACE site, Agrell *et al.* (2005) examined the effects of ambient and elevated concentrations of atmospheric CO<sub>2</sub> (360 ppm and 560 ppm) and O<sub>3</sub> (35-60 ppb and 52-90 ppb) on the foliar chemistry of paper birch trees, as well as the impacts of these effects on the host plant preferences of forest tent caterpillar larvae, finding that the mean condensed tannin concentration of the birch tree leaves was 18% greater in the elevated CO<sub>2</sub> and O<sub>3</sub> treatment than in the ambient CO<sub>2</sub> and O<sub>3</sub> treatment. In addition, they state that "the only chemical component showing a somewhat consistent covariation with larval preferences was condensed tannins," noting that "the tree becoming relatively less preferred as a result of CO<sub>2</sub> or O<sub>3</sub> treatment was in general also the one for which average levels of condensed tannins were most positively (or least negatively) affected by that treatment."

In light of these findings, it is logical to presume that as atmospheric concentrations of CO<sub>2</sub> and O<sub>3</sub> continue to rise, the increase in condensed tannin concentration likely to occur in the foliage of birch trees should lead to their leaves becoming less preferred for consumption by the dreaded forest tent caterpillar, which according to Agrell *et al.* is "an eruptive generalist defoliator in North American hardwood forests, causing extensive damage during outbreak years (Fitzgerald, 1995)." Also, because the amount of methane expelled in the breath of ruminants is an inverse function of the condensed tannin concentration of the foliage they consume, the higher birch-foliage tannin concentrations likely to prevail in a high-CO<sub>2</sub> world of the future should result in less methane being released to the atmosphere via ruminants browsing on the foliage of birch trees, which phenomenon should act to decrease the impetus for methane-induced global warming.

In conclusion, it appears that elevated concentrations of atmospheric CO<sub>2</sub> tend to increase leaf and fine-root tannin concentrations of birch trees, and that this phenomenon tends to (1) protect the trees' foliage from predation by voracious insect herbivores, (2) protect the trees' roots from soil-borne pathogens and herbivores, (3) enhance the sequestration of carbon in forest soils, and (4) reduce methane emissions from ruminants that might nibble on the trees' foliage.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/t/tanninsbirch.php>.

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### 6.7.9.3. Oak Trees

How do rising air temperatures and atmospheric CO<sub>2</sub> concentrations affect the leaf tannin concentrations of oak trees? In this section we broach this question as it applies to several different species of oak, including myrtle oak (*Quercus myrtifolia* Wild.), pedunculate oak (*Quercus robur* L.), sand live oak (*Quercus geminata* Small) and Chapman's oak (*Quercus chapmanii* Sargent).

Dury *et al.* (1998) grew four-year-old pedunculate oak trees in pots within greenhouses maintained at ambient and twice-ambient atmospheric CO<sub>2</sub> concentrations in combination with ambient and elevated (ambient plus 3°C) air temperatures for approximately one year. This work revealed that elevated CO<sub>2</sub> had only minor and contrasting direct effects on leaf palatability: a temporary increase in foliar phenolic concentrations and decreases in leaf

toughness and nitrogen content. The elevated temperature treatment, on the other hand, significantly reduced leaf palatability, because *oak leaf toughness increased as a consequence of temperature-induced increases in condensed tannin concentrations*. As a result, the researchers concluded that "a 3°C rise in temperature might be expected to result in prolonged larval development, increased food consumption, and reduced growth" for herbivores feeding on oak leaves in a CO<sub>2</sub>-enriched and warmer world of the future.

In a radically different type of experiment, Cornelissen *et al.* (2003) studied fluctuating asymmetry in the leaves of two species of sclerophyllous oaks - myrtle oak (*Quercus myrtifolia*) and sand live oak (*Quercus geminata*) - that dominate a native scrub-oak community at the Kennedy Space Center, Titusville, Florida (USA), which has served as the base of operations for a number of important open-top-chamber investigations of the effects of a 350-ppm increase in atmospheric CO<sub>2</sub> concentration on this unique ecosystem; and to provide a little background for their study, we note that *fluctuating asymmetry* is the terminology used to describe small variations from perfect symmetry in otherwise bilaterally symmetrical characters in an organism (Moller and Swaddle, 1997), which asymmetry is believed to arise as a consequence of developmental instabilities experienced during ontogeny that may be caused by various stresses, including both genetic and environmental factors (Moller and Shykoff, 1999).

Based on measurements of (1) distances from the leaf midrib to the left and right edges of the leaf at its widest point and (2) leaf areas on the left and right sides of the leaf midrib, Cornelissen *et al.* determined that "asymmetric leaves were less frequent in elevated CO<sub>2</sub>, and, when encountered, they were less asymmetric than leaves growing under ambient CO<sub>2</sub>." In addition, they found that "*Q. myrtifolia* leaves under elevated CO<sub>2</sub> were 15.0% larger than in ambient CO<sub>2</sub> and *Q. geminata* leaves were 38.0% larger in elevated CO<sub>2</sub> conditions." As a bonus, they also determined that "elevated CO<sub>2</sub> significantly increased tannin concentration for both *Q. myrtifolia* and *Q. geminata* leaves" and that "asymmetric leaves contained significantly lower concentrations of tannins than symmetric leaves for both *Q. geminata* and *Q. myrtifolia*."

In commenting on their primary findings of *reduced percentages* of leaves experiencing asymmetry in the presence of elevated levels of atmospheric CO<sub>2</sub> and the *lesser degree* of asymmetry exhibited by affected leaves in the elevated CO<sub>2</sub> treatment, Cornelissen *et al.* say that "a possible explanation for this pattern is the fact that, in contrast to other environmental stresses, which can cause negative effects on plant growth, the predominant effect of elevated CO<sub>2</sub> on plants is to promote growth with consequent reallocation of resources (Docherty *et al.*, 1996)." Another possibility they discuss "is the fact that CO<sub>2</sub> acts as a plant fertilizer," and, as a result, that "elevated CO<sub>2</sub> ameliorates plant stress compared with ambient levels of CO<sub>2</sub>," which is one of the well-documented biological benefits of atmospheric CO<sub>2</sub> enrichment (Idso and Idso, 1994).

With respect to the ancillary finding of CO<sub>2</sub>-induced increases in tannin concentrations in the leaves of both oak species (a mean increase of approximately 35% for *Q. myrtifolia* and 43% for *Q. geminata*), we note that this phenomenon may provide the two species with greater

protection against herbivores, and that part of that protection may be associated with the observed CO<sub>2</sub>-induced reductions in the amount and degree of asymmetry in the leaves of the CO<sub>2</sub>-enriched trees. Consistent with this hypothesis, for example, Stiling *et al.* (1999, 2003) found higher abundances of leaf miners in the leaves of the trees in the ambient CO<sub>2</sub> chambers, where asymmetric leaves were more abundant, while in the current study it was determined that leaf miners attacked asymmetric leaves more frequently than would be expected by chance alone in both CO<sub>2</sub> treatments.

In a subsequent study conducted at the Kennedy Space Center's scrub-oak community, Hall *et al.* (2005b) evaluated foliar quality and herbivore damage in three oaks (*Q. myrtifolia*, *Q. chapmanii* and *Q. geminata*) plus the nitrogen-fixing legume *Galactia elliotii* at three-month intervals from May 2001 to May 2003, at which times samples of undamaged leaves were removed from each of the four species in all chambers and analyzed for various chemical constituents, while 200 randomly selected leaves of each species in each chamber were scored for the presence of six types of herbivore damage. Analyses of the data thereby obtained indicated that for condensed tannins, hydrolyzable tannins, total phenolics and lignin, in *all four species* there were *always* greater concentrations of *all four leaf constituents* in the CO<sub>2</sub>-enriched leaves, with across-species mean increases of 6.8% for condensed tannins, 6.1% for hydrolyzable tannins, 5.1% for total phenolics and 4.3% for lignin. In addition, there were large CO<sub>2</sub>-induced decreases in *all* leaf damage categories among *all* species: chewing (-48%), mines (-37%), eye spot gall (-45%), leaf tier (-52%), leaf mite (-23%) and leaf gall (-16%). Hall *et al.* thus concluded that the changes they observed in leaf chemical constituents and herbivore damage "suggest that damage to plants may decline as atmospheric CO<sub>2</sub> levels continue to rise."

Last of all, and largely overlapping the investigation of Hall *et al.* (2005b), was the study of Hall *et al.* (2005a), who evaluated the effects of the Kennedy Space Center experiment's extra 350 ppm of CO<sub>2</sub> on litter quality, herbivore activity, and their interactions, over the three-year-period 2000-2002. This endeavor indicated, in their words, that "changes in litter chemistry from year to year were far larger than effects of CO<sub>2</sub> or insect damage, suggesting that these may have only minor effects on litter decomposition." The one *exception* to this finding was that "condensed tannin concentrations increased under elevated CO<sub>2</sub> regardless of species, herbivore damage, or growing season," rising by 11% in 2000, 18% in 2001 and 41% in 2002 as a result of atmospheric CO<sub>2</sub> enrichment, as best we can determine from the researchers' bar graphs. Also, the five scientists report that "lepidopteran larvae can exhibit slower growth rates when feeding on elevated CO<sub>2</sub> plants (Fajer *et al.*, 1991) and become more susceptible to pathogens, parasitoids, and predators (Lindroth, 1996; Stiling *et al.*, 1999)," noting further that at their field site, "which hosts the longest continuous study of the effects of elevated CO<sub>2</sub> on insects, herbivore populations decline markedly under elevated CO<sub>2</sub> (Stiling *et al.*, 1999, 2002, 2003; Hall *et al.*, 2005b)."

In conclusion, it would appear that the large and continuous enhancement of condensed tannin concentrations in oak tree foliage produced in CO<sub>2</sub>-enriched air is a good omen for people worried about greenhouse gas-induced global warming, because methane emissions from ruminants feeding on foliage rich in condensed tannins tend to be lower than methane

emissions from ruminants feeding on foliage of lower tannin concentration. In addition, the marked tannin-induced declines in herbivore populations observed in CO<sub>2</sub>-enriched open-top-chamber studies bodes well for the ability of earth's vegetation to better resist herbivore attacks as the air's CO<sub>2</sub> content continues to climb.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/t/tanninsoak.php>.

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### 6.7.10. Worms

Perhaps the best known worm in the world is the common earthworm. How will it be affected as the air's CO<sub>2</sub> content continues to climb, and how will its various responses affect the biosphere? What about other worms? How will they fare in a CO<sub>2</sub>-enriched world of the future, and what will be the results of their responses? Last of all -- which question we shall address first of all -- why do we even care?

"Earthworms," in the words of Edwards (1988), "play a major role in improving and maintaining the fertility, structure, aeration and drainage of agricultural soils." As noted by Sharpley *et al.* (1988), for example, "by ingestion and digestion of plant residue and subsequent egestion of cast material, earthworms can redistribute nutrients in a soil and enhance enzyme activity, thereby increasing plant availability of both soil and plant residue nutrients," as others have also demonstrated (Bertsch *et al.*, 1988; McCabe *et al.*, 1988; Zachmann and Molina, 1988). Likewise, Kemper (1988) describes how "burrows opened to the surface by surface-feeding worms provide drainage for water accumulating on the surface during intense rainfall," noting that "the highly compacted soil surrounding the expanded burrows has low permeability to water which often allows water to flow through these holes for a meter or so before it is sorbed into the surrounding soil." Hall and Dudas (1988) additionally report that the presence of earthworms appears to mitigate the deleterious effects of certain soil toxins; while Logsdon and Lindon (1988) describe a number of other beneficial effects of earthworms, including (1) enhancement of soil aeration, since under wet conditions earthworm channels do not swell shut as many soil cracks do, (2) enhancement of soil water uptake, since roots can explore deeper soil layers by following earthworm channels, and (3) enhancement of nutrient uptake, since earthworm casts and channel walls have a more neutral pH and higher available nutrient level than bulk soil. Hence, we care about what happens to earthworms as the air's CO<sub>2</sub> content rises because of the many important services they provide for earth's plant life.

So how might rising atmospheric CO<sub>2</sub> concentrations impact earthworms? Edwards (1988) says that "the most important factor in maintaining good earthworm *populations* [our italics] in agricultural soils is that there be adequate availability of organic matter," while Hendrix *et al.*

(1988) and Kladvikó (1988) report that greater levels of plant productivity promote greater levels of earthworm *activity*. Consequently, since the most ubiquitous and powerful effect of atmospheric CO<sub>2</sub> enrichment is its stimulation of plant productivity, which leads to enhanced organic matter delivery to soils, it logically follows that this *aerial fertilization effect* of the ongoing rise in the air's CO<sub>2</sub> content should significantly increase earthworm populations and amplify the many beneficial services they provide for plants.

Then there's the second most significant and common impact of atmospheric CO<sub>2</sub> enrichment on plants: its *antitranspirant effect*, whereby elevated levels of atmospheric CO<sub>2</sub> reduce leaf stomatal apertures and slow the rate of evaporative water loss from the vast bulk of earth's vegetation. Both growth chamber studies and field experiments that have studied this phenomenon provide voluminous evidence that it often leads to increased soil water contents in many terrestrial ecosystems, which is also something earthworms seem to love, i.e., plenty of soil moisture.

In light of these many proven facts, it should not have been surprising that when Zaller and Arnone (1997) fumigated open-top and -bottom chambers they established in a calcareous grassland near Basal, Switzerland with air of either 350 or 600 ppm CO<sub>2</sub> for an entire growing season, they found that the mean annual soil moisture content in the CO<sub>2</sub>-enriched chambers was 10% greater than that observed in the ambient-air chambers; and because rates of surface cast production by earthworms are typically positively correlated with soil moisture content, they found that cumulative surface cast production after only one year was 35% greater in the CO<sub>2</sub>-enriched chambers than in the control chambers. In addition, because earthworm casts are rich in organic carbon and nitrogen, the cumulative amount of these important nutrients on a per-land-area basis was found to be 28% greater in the CO<sub>2</sub>-enriched chambers than it was in the ambient-air chambers. And in a subsequent study of the same grassland, Zaller and Arnone (1999) found that plants growing in close proximity to the earthworm casts produced more biomass than similar plants growing further away from them. What is more, they found that the CO<sub>2</sub>-induced *growth stimulation* experienced by the various grasses was also greater for those plants growing nearer the earthworm casts.

The upshot of these various observations is that atmospheric CO<sub>2</sub> enrichment sets in motion a self-enhancing cycle of positive biological phenomena, whereby increases in the air's CO<sub>2</sub> content (1) stimulate plant productivity and (2) reduce plant evaporative water loss, which results in (1) more organic matter entering the soil and (2) a longer soil moisture retention time and/or greater soil water contents, all of which factors lead to the development of larger and more active earthworm populations, which enhance many important soil properties, including fertility, structure, aeration and drainage, which improved properties further enhance the growth of the plants whose CO<sub>2</sub>-induced increase in productivity was the factor that started the whole series of processes on the road to a higher level of activity in the first place, and so on.

But the good news doesn't end there. As Jongmans *et al.* (2003) point out, "the rate of organic matter decomposition can be decreased in worm casts compared to bulk soil aggregates (Martin, 1991; Haynes and Fraser, 1998)." Hence, on the basis of these studies and their own

micro-morphological investigation of structural development and organic matter distribution in two calcareous marine loam soils on which pear trees had been grown for 45 years (one of which soils exhibited little to no earthworm activity and one of which exhibited high earthworm activity, due to different levels of heavy metal contamination of the soils as a consequence of the prior use of different amounts of fungicides), they concluded that "earthworms play an important role in the intimate mixing of organic residues and fine mineral soil particles and the formation of organic matter-rich micro-aggregates and can, therefore, contribute to physical protection of organic matter, thereby slowing down organic matter turnover and increasing the soil's potential for carbon sequestration." Put more simply, atmospheric CO<sub>2</sub> enrichment that stimulates the activity of earthworms also leads to more -- and more *secure* -- sequestration of carbon in earth's soils, thereby reducing the potential for CO<sub>2</sub>-induced global warming.

Two additional studies have further demonstrated the active role worms play in helping earth's soils store and preserve carbon. Don *et al.* (2008) studied the effects of *anecic earthworms* -- which generally inhabit a single vertical burrow throughout their entire lives that can be as much as five meters in depth, but is generally in the range of one to two meters -- on soil carbon stocks and turnover via analyses of enzyme activity, stable isotopes, nuclear magnetic resonance spectroscopy, and the <sup>14</sup>C age of their burrow linings. The results of their study indicated that "the carbon distribution in soils is changed by anecic earthworms' activity with more carbon stored in the subsoil where earthworms slightly increase the carbon stocks." In this regard they also state that "the translocation of carbon from [the] organic layer to the subsoil will decrease the carbon vulnerability to mineralization," since "carbon in the organic layer and the surface soil is much more prone to disturbances with rapid carbon loss than subsoil carbon."

Lastly, Bossuyt *et al.* (2007) conducted a pair of experiments designed to investigate "at what scale and how quickly earthworms manage to protect SOM." In the first experiment, soil aggregate size distribution together with total C and <sup>13</sup>C were measured in three treatments - control soil, soil + <sup>13</sup>C-labeled sorghum leaf residue, and soil + <sup>13</sup>C-labeled residue + earthworms - after a period of 20 days incubation, where earthworms were added after the eighth day. In the second experiment, they determined the protected C and <sup>13</sup>C pools inside the newly-formed casts and macro- and micro-soil-aggregates. Results indicated that the proportion of large water-stable macroaggregates was on average 3.6 times greater in the soil-residue samples that contained earthworms than in those that lacked earthworms, and that the macroaggregates in the earthworm treatment contained approximately three times more sequestered carbon. What is more, the earthworms were found to form "a significant pool of protected C in microaggregates within large macroaggregates after 12 days of incubation," thereby demonstrating the rapidity with which earthworms perform their vital function of sequestering carbon in soils when plant residues become available to them.

But there's still *more* to the story of CO<sub>2</sub> and worms. In an intriguing research paper published in *Soil Biology & Biochemistry*, Cole *et al.* (2002) report that "in the peatlands of northern England, which are classified as blanket peat, it has been suggested that the potential effects of global warming on carbon and nutrient dynamics will be related to the activities of dominant



soil fauna, and especially enchytraeid worms." In harmony with these ideas, Cole *et al.* say they "hypothesized" that warming would lead to increased enchytraeid worm activity, which would lead to higher grazing pressure on microbes in the soil; and since enchytraeid grazing has been observed to enhance microbial activity (Cole *et al.*, 2000), they further hypothesized that more carbon would be liberated in dissolved organic form, "supporting the view that global warming will increase carbon loss from blanket peat ecosystems."

The scientists next describe how they constructed small microcosms from soil and litter they collected near the summit of Great Dun Fell, Cumbria, England. Subsequent to "defaunating" this material by reducing its temperature to -80°C for 24 hours, they thawed and inoculated it with native soil microbes, after which half of the microcosms were incubated in the dark at 12°C and half at 18°C, the former of which temperatures was approximately equal to mean August soil temperature at a depth of 10 cm at the site of soil collection, while the latter was said by them to be "close to model predictions for soil warming that might result from a doubling of CO<sub>2</sub> in blanket peat environments."

Ten seedlings of an indigenous grass of blanket peat were then transplanted into each of the microcosms, while 100 enchytraeid worms were added to each of half of the mini-ecosystems. These procedures resulted in the creation of four experimental treatments: ambient temperature, ambient temperature + enchytraeid worms, elevated temperature, and elevated temperature + enchytraeid worms. The resulting 48 microcosms - sufficient to destructively harvest three replicates of each treatment four different times throughout the course of the 64-day experiment - were arranged in a fully randomized design and maintained at either 12 or 18°C with alternating 12-hour light and dark periods. In addition, throughout the entire course of the study, the microcosms were given distilled water every two days to maintain their original weights.

So what did the researchers find? First of all, and *contrary to their hypothesis*, elevated temperature *reduced* the ability of the enchytraeid worms to enhance the loss of carbon from the microcosms. At the normal ambient temperature, for example, the presence of the worms enhanced dissolved organic carbon (DOC) loss by 16%, while at the elevated temperature expected for a doubling of the air's CO<sub>2</sub> content, the worms had *no effect at all* on DOC. In addition, Cole *et al.* note that "warming may cause drying at the soil surface, forcing enchytraeids to burrow to deeper subsurface horizons." Hence, since the worms are known to have little influence on soil carbon dynamics below a depth of 4 cm (Cole *et al.*, 2000), they concluded that this additional consequence of warming would *further* reduce the ability of enchytraeids to enhance carbon loss from blanket peatlands.

In summarizing their findings, Cole *et al.* say that "the soil biotic response to warming in this study was negative." That is, it was of such a nature that it resulted in a reduced loss of carbon to the atmosphere, which would tend to slow the rate of rise of the air's CO<sub>2</sub> content, just as was suggested by the results of the study of Jongmans *et al.*

In concluding this summary of research results related to the direct and indirect effects of atmospheric CO<sub>2</sub> enrichment on various types of worms and their subsequent activities that (1) amplify the positive effects of CO<sub>2</sub> on plants and (2) reduce the negative effects of CO<sub>2</sub> on climate, we briefly recount the findings of Yeates *et al.* (2003), who report a number of interesting results they obtained from a season-long FACE study of a 30-year-old New Zealand pasture, where three experimental plots had been maintained at the ambient atmospheric CO<sub>2</sub> concentration of 360 ppm and three others at a concentration of 475 ppm (a CO<sub>2</sub> enhancement of only 32%) for a period of four to five years. The pasture contained about twenty species of plants, including C<sub>3</sub> and C<sub>4</sub> grasses, legumes and forbs; but the scientists' attention was focused more on what happened to the microfauna inhabiting the soil in which the plants grew than on the plants themselves.

Nematode populations increased significantly in response to the 32% increase in the air's CO<sub>2</sub> concentration. Of the various feeding groups studied, Yeates *et al.* report that the relative increase "was lowest in bacterial-feeders (27%), slightly higher in plant (root) feeders (32%), while those with delicate stylets (or narrow lumens; plant-associated, fungal-feeding) increased more (52% and 57%, respectively)." The greatest nematode increases, however, were recorded among omnivores (97%) and predators (105%). Most dramatic of all, root-feeding populations of the *Longidorus* nematode taxon rose by a whopping 330%. Also increasing in abundance were earthworms: *Aporrectodea caliginosa* by 25% and *Lumbricus rubellus* by 58%. Enchytraeids, on the other hand, *decreased* in abundance, by approximately 30%.

What are the ramifications of these observations? With respect to earthworms, Yeates *et al.* note that just as was found in the studies cited in the first part of this review, the introduction of lumbricids has been demonstrated to improve soil conditions in New Zealand pastures (Stockdill, 1982), which obviously helps pasture plants to grow better. Hence, the CO<sub>2</sub>-induced increase in earthworm numbers observed in Yeates *et al.*'s study would be expected to do more of the same, while the reduced abundance of enchytraeids they documented in the CO<sub>2</sub>-enriched pasture would supposedly lead to less carbon being released to the air from the soil, as per the known ability of enchytraeids to promote carbon loss from British peat lands under current temperatures.

In summary, it would appear that the lowly earthworm and still lowlier soil nematodes respond to increases in the air's CO<sub>2</sub> content, via a number of plant-mediated phenomena, in ways that further enhance the positive effects of atmospheric CO<sub>2</sub> enrichment on plant growth and development, while at the same time helping to sequester more carbon more securely in the soil and thereby reducing the potential for CO<sub>2</sub>-induced global warming.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/e/earthworms.php>.

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### **6.8. Greening of the Earth**

Over two decades ago, Idso (1986) published a small item in *Nature* advancing the idea that the aerial fertilization effect of the CO<sub>2</sub> that is liberated by the burning of coal, gas and oil was destined to dramatically enhance the productivity of earth's vegetation. In fact, in a little book he had published four years earlier (Idso, 1982), he had predicted that "CO<sub>2</sub> effects on both the managed and unmanaged biosphere will be overwhelmingly positive," if not "mind-boggling." And in a monograph based on a lecture he gave nine years later (Idso, 1995), he said that "we appear to be experiencing the initial stages of what could truly be called a *rebirth of the biosphere*, the beginnings of a biological rejuvenation that is without precedent in all of human history." Consequently, and in light of the fact that Idso's worldview is nearly the exact *opposite* of the apocalyptic vision promulgated by climate alarmists, it is instructive to see what real-world observations reveal about the matter; and in this section we do so for various regions of the world, and for the globe as a whole.

Additional information on this topic, including reviews not discussed here, can be found at [http://www.co2science.org/subject/g/subject\\_g.php](http://www.co2science.org/subject/g/subject_g.php) under the heading Greening of the Earth.

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### 6.8.1. Africa

In an article by Fred Pearce that was posted on the website of *New Scientist* magazine on 16 September 2002 entitled "Africa's deserts are in 'spectacular' retreat," we were told the story of vegetation reclaiming great tracts of barren land across the entire southern edge of the Sahara. This information likely came as a bit of a surprise to many, since the United Nations Environment Program had reported to the World Summit on Sustainable Development in Johannesburg, South Africa in August of that year that over 45% of the continent was experiencing severe desertification. The world of nature, however, told a vastly different story. Pearce began his eye-opening article by stating that "the southern Saharan desert is in retreat, making farming viable again in what were some of the most arid parts of Africa," noting that "Burkina Faso, one of the West African countries devastated by drought and advancing deserts 20 years ago, is growing so much greener that families who fled to wetter coastal regions are starting to go home."

And the good news was not confined to Burkina Faso. "Vegetation," according to Pearce, "is ousting sand across a swathe of land stretching from Mauritania on the shores of the Atlantic to Eritrea 6000 kilometers away on the Red Sea coast." What is more, besides being widespread in space, the greening was widespread in time, having been happening since at least the mid-1980s.

Quoting Chris Reij of the Free University of Amsterdam, Pearce wrote that "aerial photographs taken in June show 'quite spectacular regeneration of vegetation' in northern Burkina Faso." The data indicated the presence of more trees for firewood and more grassland for livestock. In addition, a survey that Reij was collating showed, according to Pearce, "a 70 percent increase in yields of local cereals such as sorghum and millet in one province in recent years." Also studying the area was Kjeld Rasmussen of the University of Copenhagen, who reported that since the 1980s there had been a "steady reduction in bare ground" with "vegetation cover, including bushes and trees, on the increase on the dunes."

Pearce also reported on the work of a team of geographers from Britain, Sweden and Denmark that had spent much of the prior summer analyzing archived satellite images of the Sahel. Citing Andrew Warren of University College London as a source of information on this study, he said the results showed "that 'vegetation seems to have increased significantly' in the past 15 years, with major regrowth in southern Mauritania, northern Burkina Faso, north-western Niger, central Chad, much of Sudan and parts of Eritrea."

Should these findings take us by surprise? Not in the least, as Nicholson *et al.* (1998) reported in a study of a series of satellite images of the Central and Western Sahel that were taken from 1980 to 1995, they could find no evidence of any overall expansion of deserts and no drop in

the rainfall use efficiency of native vegetation. In addition, in a satellite study of the *entire* Sahel from 1982 to 1990, Prince *et al.* (1998) actually detected a steady *rise* in rainfall use efficiency, suggesting that plant productivity and coverage of the desert had actually *increased* during this period.

That the greening phenomenon has continued apace is borne out by the study of Eklundh and Olsson (2003), who analyzed Normalized Difference Vegetation Index (NDVI) data obtained from the U.S. National Oceanic and Atmospheric Administration's satellite-borne Advanced Very High Resolution Radiometer whenever it passed over the African Sahel for the period 1982-2000. As they describe their findings, "strong positive change in NDVI occurred in about 22% of the area, and weak positive change in 60% of the area," while "weak negative change occurred in 17% of the area, and strong negative change in 0.6% of the area." In addition, they report that "integrated NDVI has increased by about 80% in the areas with strong positive change," while in areas with weak negative change, "integrated NDVI has decreased on average by 13%." The primary story told by these data, therefore, is one of strong positive trends in NDVI for large areas of the African Sahel over the last two decades of the 20th century; and Eklundh and Olsson conclude that the "increased vegetation, as suggested by the observed NDVI trend, could be part of the proposed tropical sink of carbon."

Due to the stunning increase in vegetation over the past quarter-century in the Sahel, the African region was recently featured in a special issue of the *Journal of Arid Environments* entitled "The 'Greening' of the Sahel." Therein, Anyamba and Tucker (2005) describe their development of an NDVI history of the region for the period 1981-2003. Comparing this history with the precipitation history of the Sahel developed by Nicholson (2005), they found that "the persistence and spatial coherence of drought conditions during the 1980s is well represented by the NDVI anomaly patterns and corresponds with the documented rainfall anomalies across the region during this time period." In addition, they report that "the prevalence of greener than normal conditions during the 1990s to 2003 follows a similar increase in rainfall over the region during the last decade."

In another analysis of NDVI and rainfall data in the same issue of the *Journal of Arid Environments*, Olsson *et al.* (2005) also report finding "a consistent trend of increasing vegetation greenness in much of the region," which they describe as "remarkable." And they say that increasing rainfall over the last few years "is certainly one reason" for the greening phenomenon. However, they find that the increase in rainfall "does not fully explain" the increase in greenness.

For one thing, the three Swedish scientists note that "only eight out of 40 rainfall observations showed a statistically significant increase between 1982-1990 and 1991-1999." In addition, they report that "further analysis of this relationship does not indicate an overall relationship between rainfall increase and vegetation trend." So what else could be driving the increase in greenness?

Olsson *et al.* suggest that "another potential explanation could be improved land management, which has been shown to cause similar changes in vegetation response elsewhere (Runnstrom, 2003)." However, in more detailed analyses of Burkina Faso and Mali, where production of millet rose by 55% and 35%, respectively, since 1980, they could find "no clear relationship" between agricultural productivity and NDVI, which argues against the land management explanation.

A third speculation of Olsson *et al.* is that the greening of the Sahel could be caused by increasing rural-to-urban migration. In this scenario, widespread increases in vegetation occur as a result of "reduced area under cultivation," due to a shortage of rural laborers, and/or "increasing inputs on cropland," such as seeds, machinery and fertilizers made possible by an increase in money sent home to rural households by family members working in cities. However, Olsson *et al.* note that "more empirical research is needed to verify this [hypothesis]."

About the only thing left is what Idso (1982, 1986, 1995) has suggested, i.e., that the *aerial fertilization effect* of the ongoing rise in the air's CO<sub>2</sub> concentration (which greatly enhances vegetative productivity) and its *anti-transpiration effect* (which enhances plant water-use efficiency and enables plants to grow in areas that were once too dry for them) are the major players in the greening phenomenon. Be that as it may, and *whatever* was the reason for the greening of the Sahel over the past quarter-century, it is clear that in spite of what the world's climate alarmists claim were *unprecedented increases* in the "twin evils" of anthropogenic CO<sub>2</sub> emissions and global warming, the Sahel experienced an increase in vegetative prowess that was *truly*, as Olsson *et al.* write, "remarkable."

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/g/africagreen.php>.

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### 6.8.2. Asia

We begin a review of Asia with the modeling work of Liu *et al.* (2004), who derived detailed estimates of the economic impact of predicted climate change on agriculture in China, utilizing county-level agricultural, climate, social, economic and edaphic data for 1275 agriculture-dominated counties for the period 1985-1991, together with the outputs of three general circulation models of the atmosphere that were based on five different scenarios of anthropogenic CO<sub>2</sub>-induced climate change that yielded a mean countrywide temperature increase of 3.0°C and a mean precipitation increase of 3.9% for the 50-year period ending in AD 2050. In doing so, they determined that "*all of China* [our italics] would *benefit* [our italics] from climate change in most scenarios." In addition, they state that "the effects of CO<sub>2</sub> fertilization should [also] be included, for some studies indicate that this may produce a significant increase in yield," an increase that is *extremely* well established.

The great significance of these findings is readily grasped when it is realized, in Liu *et al.*'s words, that "China's agriculture has to feed more than one-fifth of the world's population, and, historically, China has been famine prone." As one example of this fact, they report that "as recently as the late 1950s and early 1960s a great famine claimed about thirty million lives (Ashton *et al.*, 1984; Cambridge History of China, 1987)." Acting together, therefore, it is clear that the increases in China's agricultural production estimated to result from the direct effects of increased anthropogenic CO<sub>2</sub> emissions *plus* the increases due to the changes in temperature and precipitation typically predicted to result from these emissions could well prove the deciding factor in determining whether China's population *will* or *will not* be able to adequately feed itself at the midpoint of the current century, which could well spell the difference between whether the world of that day will be peaceful or embroiled in conflict.

Moving from agro-ecosystems to natural ones, Su *et al.* (2004) used an ecosystem process model to explore the sensitivity of the net primary productivity (NPP) of an oak forest near Beijing (China) to the global climate changes projected to result from a doubling of the atmosphere's CO<sub>2</sub> concentration from 355 to 710 ppm. The results of this work suggested that



the aerial fertilization effect of the specified increase in the air's CO<sub>2</sub> content would raise the forest's NPP by 14.0%, that a concomitant temperature increase of 2°C would boost the NPP increase to 15.7%, and that adding a 20% increase in precipitation would push the NPP increase all the way to 25.7%. Last of all, they calculated that a 20% increase in precipitation and a 4°C increase in temperature would also boost the forest's NPP by 25.7%.

In contrast to typical climate-alarmist contentions, therefore, it is clear that many projections of Asian ecosystem responses to potential increases in atmospheric CO<sub>2</sub> and temperature are *not* catastrophically negative, even when the projected increases in air temperature are as large as the 4°C rise investigated by Su *et al.* In fact, as in the case of their analysis, many of the responses are *positive*, and strongly so. One of the reasons for this discrepancy between real-world *fact* and climate-alarmist *fiction* is that climate-alarmists typically disregard the many beneficial effects of concomitant atmospheric CO<sub>2</sub> enrichment, including the ability of elevated levels of atmospheric CO<sub>2</sub> to significantly increase plant growth and water use efficiency, as well as their tendency to alter the physiology of plants to where they actually *prefer* warmer temperatures, which phenomenon is expressed as a CO<sub>2</sub>-induced increase in the temperature at which plants photosynthesize most effectively.

Related evidence for the reality of these phenomena is presented in the work of Grunzweig *et al.* (2003), who tell the tale of the Yatir forest (a 2800-hectare stand of Aleppo and other pine trees) that had been planted some 35 years earlier at the edge of the Negev Desert in Israel. An intriguing aspect of this particular forest, which they characterize as growing in poor soil of only 0.2 to 1.0 meter's depth above chalk and limestone, is that although it is located in an arid part of Asia that receives less annual precipitation than all of the other scores of FluxNet stations in the global network of micrometeorological tower sites that use eddy covariance methods to measure exchanges of CO<sub>2</sub>, water vapor and energy between terrestrial ecosystems and the atmosphere (Baldocchi *et al.*, 2001), the forest's annual net ecosystem CO<sub>2</sub> exchange was just as high as that of many high-latitude boreal forests and actually higher than that of most temperate forests.

How could this possibly be?

Grunzweig *et al.* note that the increase in atmospheric CO<sub>2</sub> concentration that has occurred since pre-industrial times should have improved water use efficiency (WUE) in most plants by increasing the ratio of CO<sub>2</sub> fixed to water lost via evapotranspiration. That this hypothesis is indeed correct has been demonstrated by Leavitt *et al.* (2003) within the context of the long-term atmospheric CO<sub>2</sub> enrichment experiment of Idso and Kimball (2001) on sour orange trees. It has also been confirmed in nature by Feng (1999), who obtained identical (to the study of Leavitt *et al.*) CO<sub>2</sub>-induced WUE responses for 23 groups of naturally-occurring trees scattered across western North America over the period 1800-1985, which response, Feng concludes, "would have caused natural trees in arid environments to grow more rapidly, acting as a carbon sink for anthropogenic CO<sub>2</sub>," which is exactly what Grunzweig *et al.* found to be happening in the Yatir forest on the edge of the Negev Desert. In addition, the latter researchers report that "reducing water loss in arid regions improves soil moisture conditions, decreases water stress

and extends water availability," which "can indirectly increase carbon sequestration by influencing plant distribution, survival and expansion into water-limited environments."

In light of these several observations, it is only natural to expect that as atmospheric CO<sub>2</sub> concentrations and air temperatures rise hand-in-hand, both natural and agro-ecosystems would exhibit ever-increasing rates of net primary production ... *and so they do*, as has been demonstrated by a number of data-driven studies.

Based primarily on satellite-derived Normalized Difference Vegetation Index (NDVI) data, Zhou *et al.* (2001) found that from July 1981 to December 1999, between 40 and 70° N latitude, there was a persistent increase in growing season vegetative productivity in excess of 12% over a broad contiguous swath of Asia stretching from Europe through Siberia to the Aldan plateau, where almost 58% of the land is forested. And in a companion study, Bogaert *et al.* (2002) determined that this productivity increase occurred at a time when this vast Asian region showed an overall warming trend "with negligible occurrence of cooling."

In another study that also included a portion of Europe, Lapenis *et al.* (2005) analyzed trends in forest biomass in all 28 ecoregions of the Russian territory, based on data collected from 1953 to 2002 within 3196 sample plots comprised of about 50,000 entries, which database, in their words, "contains all available archived and published data." This work revealed that over the period 1961-1998, as they describe it, "aboveground wood, roots, and green parts increased by 4%, 21%, and 33%, respectively," such that "the total carbon density of the living biomass stock of the Russian forests increased by ~9%." They also report there was a concomitant increase of ~11% in the *area* of Russian forests. In addition, the team of US, Austrian and Russian scientists reported that "within the range of 50-65° of latitude [the range of 90% of Russian forests], the relationship between biomass density and the area-averaged NDVI is very close to a linear function, with a slope of ~1," citing the work of Myneni *et al.* (2001). Therefore, as they continue, "changes in the carbon density of live biomass in Russian forests occur at about the same rate as the increase in the satellite-based estimate in the seasonally accumulated NDVI," which observation strengthens the findings of *all* satellite-based NDVI studies.

Returning to China for several concluding reports, we begin with the work of Brogaard *et al.* (2005), who studied the dry northern and northwestern regions of the country - including the Inner Mongolia Autonomous Region (IMAR) - which had been thought to have experienced declining vegetative productivity over the past few decades due to "increasing livestock numbers, expansion of cultivated land on erosive soils and the gathering of fuel wood and herb digging," which practices were believed to have been driven by rising living standards, which in combination with a growing population were assumed to have increased the pressure on these marginal lands. In the case of increasing grazing, for example, Brogaard *et al.* note that the total number of livestock in the IMAR increased from approximately 46 million head in 1980 to about 71 million in 1997.

To better assess the seriousness of this supposedly "ongoing land degradation process," as they describe it, the researchers adapted a satellite-driven parametric model, originally developed

for Sahelian conditions, to the central Asian steppe region of the IMAR by including "additional stress factors and growth efficiency computations." The applied model, in their words, "uses satellite sensor-acquired reflectance in combination with climate data to generate monthly estimates of gross primary production." To their great surprise, this work revealed that "despite a rapid increase in grazing animals on the steppes of the IMAR for the 1982-1999 period," their model estimates did "*not* [our italics] indicate declining biological production."

Clearly, some strong positive influence compensated for the increased human and animal pressures on the lands of the IMAR over the period of Brogaard *et al.*'s study. In this regard, they mention the possibility of increasing productivity on the agricultural lands of the IMAR, but they note that crops are grown on "only a small proportion of the total land area." Other potential contributing factors they mention are "an increase in precipitation, as well as afforestation projects." Two things that are *not* mentioned are the aerial fertilization effect and the transpiration-reducing effect of the increase in the air's CO<sub>2</sub> concentration that was experienced over the study period. Applied together, the sum of these several positive influences (and possibly others that remain unknown) was demonstrably sufficient to keep plant productivity from declining in the face of greatly increasing animal and human pressures on the lands of the IMAR from 1982 to 1999.

Also working in an area not expected to show a positive response to the "twin evils" of rising air temperatures and atmospheric CO<sub>2</sub> concentrations, Piao *et al.* (2005a) used a time series of NDVI data from 1982 to 1999, together with precipitation and temperature data, to investigate variations of desert area in China by "identifying the climatic boundaries of arid area and semiarid area, and changes in NDVI in these areas." In doing so, they discovered that "average rainy season NDVI in arid and semiarid regions both increased significantly during the period 1982-1999." Specifically, they found that the NDVI increased for 72.3% of total arid regions and for 88.2% of total semiarid regions, such that the area of arid regions decreased by 6.9% and the area of semiarid regions decreased by 7.9%. They also report that by analyzing Thematic Mapper satellite images, "Zhang *et al.* (2003) documented that the process of desertification in the Yulin area, Shannxi Province showed a decreased trend between 1987 and 1999," and that "according to the national monitoring data on desertification in western China (Shi, 2003), the annual desertification rate decreased from 1.2% in the 1950s to -0.2% at present."

Further noting that "variations in the vegetation coverage of these regions partly affect the frequency of sand-dust storm occurrence (Zou and Zhai, 2004)," Piao *et al.* concluded that "increased vegetation coverage in these areas will likely fix soil, enhance its anti-wind-erosion ability, reduce the possibility of released dust, and consequently cause a mitigation of sand-dust storms." Interestingly, in this regard, they report that "recent studies have suggested that the frequencies of strong and extremely strong sand-dust storms in northern China have significantly declined from the early 1980s to the end of the 1990s (Qian *et al.*, 2002; Zhao *et al.*, 2004)." Hence, it would appear that the dreaded climatic change claimed to have been experienced by the globe over the latter part of the 20th century was either (1) not so dreaded after all or (2) *totally dwarfed* by opposing phenomena that significantly *benefited* China, as its

lands grew ever greener during this period and its increased vegetative cover helped to stabilize its soils and throw feared desertification into reverse.

Continuing in much the same vein, Piao *et al.* (2006) investigated vegetation net primary production (NPP) derived from a carbon model (Carnegie-Ames-Stanford approach, CASA) and its interannual change in the Qinghai-Xizang (Tibetan) Plateau using 1982-1999 NDVI data and paired ground-based information on vegetation, climate, soil, and solar radiation. This work revealed that over the entire study period, NPP rose at a mean annual rate of 0.7%. However, Piao *et al.* report that "the NPP trends in the plateau over the two decades were divided into two distinguished periods: without any clear trend from 1982 to 1990 and significant increase from 1991 to 1999."

The three researchers say their findings suggest that "vegetation growth on the plateau in the 1990s has been much enhanced compared to that in [the] 1980s, consistent with the trend in the northern latitudes indicated by Schimel *et al.* (2001)." In addition, they say that "previous observational and NPP modeling studies have documented substantial evidence that terrestrial photosynthetic activity has increased over the past two to three decades in the middle and high latitudes in the Northern Hemisphere," and that "satellite-based NDVI data sets for the period of 1982-1999 also indicate consistent trends of NDVI increase," citing multiple references in support of each of these statements. Piao *et al.*'s findings, therefore, add to the growing body of evidence that reveals a significant "greening of the earth" is occurring in response to (1) the ongoing recovery of the planet from the growth-inhibiting chill of the Little Ice Age, which was likely *the coldest period of the current interglacial*, plus (2) the aerial fertilization effect of the historical and still-ongoing rise in the atmosphere's CO<sub>2</sub> concentration, as well as (3) the growth-promoting effect of anthropogenic nitrogen deposition.

Applying the same techniques, Fang *et al.* (2003) looked at the whole of China, finding that its terrestrial NPP increased by 18.7% between 1982 and 1999. Referring to this result as "an unexpected aspect of biosphere dynamics," they say that this increase "is much greater than would be expected to result from the fertilization effect of elevated CO<sub>2</sub>, and also greater than expected from climate, based on broad geographic patterns."

But is this really so?

From 1982 to 1999, the atmosphere's CO<sub>2</sub> concentration rose by approximately 27.4 ppm. Based on the procedures and reasoning described in a *CO<sub>2</sub> Science* Editorial of [18 Sep 2002](#), the aerial fertilization effect of this CO<sub>2</sub> increase could be expected to have increased the NPP of the conglomerate of forest types found in China by about 7.3%. But this increase is only a *part* of the total NPP increase we could expect, for Fang *et al.* note that "much of the trend in NPP appeared to reflect a change towards an earlier growing season," which was driven by the 1.1°C increase in temperature they found to have occurred in their region of study between 1982 and 1999.

Following this lead, we learn from the study of White *et al.* (1999) - which utilized 88 years of data (1900-1987) that were obtained from 12 different locations within the eastern U.S. deciduous forest that stretches from Charleston, SC (32.8°N latitude) to Burlington, VT (44.5°N latitude) - that a 1°C increase in mean annual air temperature increases the length of the forest's growing season by approximately five days. In addition, White *et al.* determined that a one-day extension in growing season length increased the mean forest NPP of the 12 sites they studied by an average of 1.6%. Hence, we could expect an *additional* NPP increase due to the warming-induced growing season expansion experienced in China from 1982 to 1999 of 1.6%/day x 5 days = 8.0%, which brings the total CO<sub>2</sub>-induced plus warming-induced increase in NPP to 15.3%.

Last of all, we note there is a well-documented positive synergism between increasing air temperature and CO<sub>2</sub> concentration (Idso and Idso, 1994), such that the 1°C increase in temperature experienced in China between 1982 and 1999 could *easily* boost the initial CO<sub>2</sub>-induced 7.3% NPP enhancement to the 10.7% enhancement that when combined with the 8.0% enhancement caused by the warming-induced increase in growing season length would produce the 18.7% increase in NPP detected in the satellite data.

In view of these observations, the findings of Fang *et al.* are seen to be right in line with what would be expected to result from the increases in air temperature and atmospheric CO<sub>2</sub> concentration that occurred between 1982 and 1999 in China: a dramatically stimulated terrestrial biosphere that is growing ever more productive with each passing year. This is the *true observed consequence* of the "twin evils" of the radical climate-alarmist movement (rising CO<sub>2</sub> and temperature); and it is about as opposite and far removed as one can get from the horror stories this group promulgates, i.e., that the increases in these two factors are greater threats to the well-being of the biosphere, including humanity, than either *nuclear warfare* or *world terrorism*.

Analyzing the same set of data still further, Piao *et al.* (2005b) say their results suggest that "terrestrial NPP in China increased at a rate of 0.015 Pg C yr<sup>-1</sup> over the period 1982-1999, corresponding to a total increase of 18.5%, or 1.03% annually." They also found that "during the past 2 decades the amplitude of the seasonal curve of NPP has increased and the annual peak NPP has advanced," which they say "may indirectly explain the enhanced amplitude and advanced timing of the seasonal cycle of atmospheric CO<sub>2</sub> concentration (Keeling *et al.*, 1996)," the former of which phenomena they further suggest "was probably due to the rise in atmospheric CO<sub>2</sub> concentration, elevated temperature, and increased atmospheric N and P deposition," while the latter phenomenon they attribute to "advanced spring onset and extended autumn growth owing to climate warming." We are in basic agreement on most of these points, but note that the advanced onset of what may be called *biological spring* is also fostered by the ultra-enhancement of early spring growth that is provided by the ongoing rise in the air's CO<sub>2</sub> concentration.

Citing a total of 20 scientific papers at various places in the following quote from their research report, Piao *et al.* conclude that "results from observed atmospheric CO<sub>2</sub> and O<sub>2</sub>

concentrations, inventory data, remote sensing data, and carbon process models have all suggested that terrestrial vegetation NPP of the Northern Hemisphere has increased over the past 2 decades and, as a result, the northern terrestrial ecosystems have become important sinks for atmospheric CO<sub>2</sub>." Again, we agree, and again we wonder what there is about these very impressive positive observations that inspire radical environmentalists to classify the *twin evils* of rising atmospheric CO<sub>2</sub> and temperature as *worse than nuclear warfare and global terrorism*.

In conclusion, it would appear that rather than *devastating* the landscape, the historical increases in the atmosphere's CO<sub>2</sub> concentration and temperature have actually *fostered* a significant *greening of the earth*, including that observed throughout the length and breadth of Asia.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/g/asiagreen.php>.

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### 6.8.3. Europe

Allen *et al.* (1999) analyzed sediment cores from a lake in southern Italy and from the Mediterranean Sea, developing high-resolution climate and vegetation data sets for this region over the last 102,000 years. These materials indicated that rapid changes in vegetation were well correlated with rapid changes in climate, such that complete shifts in natural ecosystems would sometimes occur over periods of less than 200 years. Over the warmest portion of the record (the Holocene), the total organic carbon content of the vegetation reached its highest level, more than doubling values experienced over the rest of the record, while other proxy indicators revealed that during the more productive woody-plant period of the Holocene, the increased vegetative cover also led to less soil erosion. The results of this study thus demonstrate that the biosphere can successfully respond to rapid changes in climate. As the 15 researchers involved in the work put it, "the biosphere was a full participant in these rapid fluctuations, contrary to widely held views that vegetation is unable to change with such rapidity." Furthermore, their work revealed that *warmer* was always *better* in terms of vegetative productivity. Thus, it is likely that future warming in this region may return it to a higher level of biological productivity than what it currently exhibits.

Osborne *et al.* (2000) used an empirically-based mechanistic model of Mediterranean shrub vegetation to address two important questions: (1) Has recent climate change, especially increased drought, negatively impacted Mediterranean shrublands? *and* (2) Has the historical



increase in the air's CO<sub>2</sub> concentration modified this impact? The data-based model they employed suggests that the warming and reduced precipitation experienced in the Mediterranean area over the past century should have had negative impacts on net primary production and leaf area index. When the measured increase in atmospheric CO<sub>2</sub> concentration experienced over the period was factored into the calculation, however, these negative influences were overpowered, with the net effect that both measures of vegetative prowess *increased*: net primary productivity by 25% and leaf area index by 7%. These results, in their words, "indicate that the recent rise in atmospheric CO<sub>2</sub> may already have had significant impacts on productivity, structure and water relations of sclerophyllous shrub vegetation, which tended to offset the detrimental effects of climate change in the region."

How can we relate this observation to climate change predictions for the earth as a whole? For a nominal doubling of the air's CO<sub>2</sub> concentration from 300 to 600 ppm, earth's mean surface air temperature is predicted by current climate models to rise by approximately 3°C, which equates to a temperature rise of 0.01°C per ppm CO<sub>2</sub>. In the case of the Mediterranean region here described, the temperature rise over the past century was quoted by Osborne *et al.* as being 0.75°C, over which period of time the air's CO<sub>2</sub> concentration rose by approximately 75 ppm, for an analogous climate response of exactly the same value: 0.01°C per ppm CO<sub>2</sub>.

With respect to model-predicted changes in earth's *precipitation* regime, a doubling of the air's CO<sub>2</sub> content is projected to lead to a modest intensification of the planet's hydrologic cycle. In the case of the Mediterranean region over the last century, however, there has been a recent tendency toward *drier* conditions. Hence, the specific case investigated by Osborne *et al.* represents a *much-worse-case* scenario than what is predicted by current climate models for the earth as a whole. Nevertheless, the area's vegetation has done even better than it did before the climatic change, thanks to the over-powering beneficial biological effects of the concurrent rise in the air's CO<sub>2</sub> content.

Cheddadi *et al.* (2001) employed a standard biogeochemical model (BIOME3) - which uses monthly temperature and precipitation data, certain soil characteristics, cloudiness, and atmospheric CO<sub>2</sub> concentration as inputs - to simulate the responses of various biomes in the region surrounding the Mediterranean Sea to changes in both climate (temperature and precipitation) and the air's CO<sub>2</sub> content. Their first step was to validate the model for two test periods: the present and 6000 years before present (BP). Recent instrumental records provided actual atmospheric CO<sub>2</sub>, temperature and precipitation data for the present period; while pollen data were used to reconstruct monthly temperature and precipitation values for 6000 years BP, and ice core records were used to determine the atmospheric CO<sub>2</sub> concentration of that earlier epoch. These efforts suggested that winter temperatures 6000 years ago were about 2°C cooler than they are now, that annual rainfall was approximately 200 mm less than today, and that the air's CO<sub>2</sub> concentration averaged 280 ppm, which is considerably less than the value of 345 ppm the researchers used to represent the present, i.e., the mid-point of the period used for calculating 30-year climate normals at the time they wrote their paper. Applying the model to these two sets of conditions, they demonstrated that "BIOME3 can be used to simulate ... the vegetation distribution under ... different climate and [CO<sub>2</sub>] conditions

than today," where  $[CO_2]$  is the abbreviation they use to represent "atmospheric  $CO_2$  concentration."

Cheddadi *et al.*'s next step was to use their validated model to explore the vegetative consequences of an increase in anthropogenic  $CO_2$  emissions that pushes the air's  $CO_2$  concentration to a value of 500 ppm and its mean annual temperature to a value  $2^\circ C$  higher than today's mean value. The basic response of the vegetation to this change in environmental conditions was "a substantial southward shift of Mediterranean vegetation and a spread of evergreen and conifer forests in the northern Mediterranean."

More specifically, in the words of the researchers, "when precipitation is maintained at its present-day level, an evergreen forest spreads in the eastern Mediterranean and a conifer forest in Turkey." Current xerophytic woodlands in this scenario become "restricted to southern Spain and southern Italy and they no longer occur in southern France." In northwest Africa, on the other hand, "Mediterranean xerophytic vegetation occupies a more extensive territory than today and the arid steppe/desert boundary shifts southward," as each vegetation zone becomes significantly more verdant than it is currently.

What is the basis for these positive developments? Cheddadi *et al.* say "the replacement of xerophytic woodlands by evergreen and conifer forests could be explained by the enhancement of photosynthesis due to the increase of  $[CO_2]$ ." Likewise, they note that "under a high  $[CO_2]$  stomata will be much less open which will lead to a reduced evapotranspiration and lower water loss, both for  $C_3$  and  $C_4$  plants," adding that "such mechanisms may help plants to resist long-lasting drought periods that characterize the Mediterranean climate."

Contrary to what is often predicted for much of the world's moisture-challenged lands, therefore, the authors were able to report that "an increase of  $[CO_2]$ , jointly with an increase of *ca.*  $2^\circ C$  in annual temperature would not lead to desertification on any part of the Mediterranean unless annual precipitation decreased drastically," where they define a *drastic* decrease as a decline of 30% or more. Equally important in this context is the fact that Hennessy *et al.* (1997) have indicated that a doubling of the air's  $CO_2$  content would in all likelihood lead to a 5 to 10% *increase* in annual precipitation at Mediterranean latitudes, which is also what is predicted for most of the rest of the world. Hence, the results of the present study - where precipitation was held constant - may validly be considered to be a *worst-case* scenario, with the *true* vegetative response being even *better* than the good-news results reported by Cheddadi *et al.*, even when utilizing what we believe to be erroneously-inflated global warming predictions.

Julien *et al.* (2006) "used land surface temperature (LST) algorithms and NDVI [Normalized Difference Vegetation Index] values to estimate changes in vegetation in the European continent between 1982 and 1999 from the Pathfinder AVHRR [Advanced Very High Resolution Radiometer] Land (PAL) dataset." This program revealed that arid and semi-arid areas (Northern Africa, Southern Spain and the Middle East) have seen their mean LST increase and NDVI decrease, while temperate areas (Western and Central Europe) have suffered a slight

decrease in LST but a more substantial increase in NDVI, especially in Germany, the Czech Republic, Poland and Belarus. In addition, parts of continental and Northern Europe have experienced either slight increases or decreases in NDVI while LST values have decreased. Considering the results in their totality, the Dutch and Spanish researchers concluded that, over the last two decades of the 20th century, "Europe as a whole has a tendency to greening," and much of it is "seeing an increase in its wood land proportion."

Working in the Komi Republic in the northeast European sector of Russia, Lopatin *et al.* (2006) (1) collected discs and cores from 151 Siberian spruce trees and 110 Scots pines from which they developed ring-width chronologies that revealed yearly changes in forest productivity, (2) developed satellite-based time series of NDVI for the months of June, July, August over the period 1982-2001, (3) correlated their site-specific ring-width-derived productivity histories with same-site NDVI time series, (4) used the resulting relationship to establish six *regional* forest productivity histories for the period 1982-2001, and (5) compared the six regional productivity trends over this period with corresponding-region temperature and precipitation trends. For all six vegetation zones of the Komi Republic, this work indicated that the 1982-2001 trends of integrated NDVI values from June to August were *positive*, and that the "increase in productivity reflected in [the] NDVI data [was] maximal on the sites with increased temperature and decreased precipitation."

In discussing their findings, the three scientists state that "several studies (Riebsame *et al.*, 1994; Myneni *et al.*, 1998; Vicente-Serrano *et al.*, 2004) have shown a recent increase in vegetation cover in different world ecosystems." What is special about their study, as they describe it, is that "in Europe, most forests are managed, except for those in northwestern Russia [the location of their work], where old-growth natural forests are dominant (Aksenov *et al.*, 2002)." Consequently, and because of their positive findings, they say we can now conclude that "productivity during recent decades also increased in relatively untouched forests," where non-management-related "climate change with lengthening growing season, increasing CO<sub>2</sub> and nitrogen deposition" are the primary determinants of changes in forest productivity.

In concluding this brief review of pertinent studies conducted in Europe, we note that within the context of today's obsession with the ongoing rise in the atmosphere's CO<sub>2</sub> content, as well as the many environmental catastrophes it has been predicted to produce, the overwhelmingly positive results that have been obtained are truly remarkable. This assessment is even *more* remarkable in light of the fact that the world's climate alarmists claim the warming of the past quarter-century was unprecedented over the last two millennia or more, and that this phenomenon is the greatest threat ever to be faced by the planet. Apparently the *plants* of Europe just don't understand the seriousness of the situation.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/g/europegreen.php>.

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#### 6.8.4. North America

In a paper entitled "Variations in northern vegetation activity inferred from satellite data of vegetation index during 1981-1999," Zhou *et al.* (2001) determined that the magnitude of the satellite-derived *normalized difference vegetation index* (NDVI) rose by 8.44% in North America over this period. Noting that the NDVI "can be used to proxy the vegetation's responses to climate changes because it is well correlated with the fraction of photosynthetically active radiation absorbed by plant canopies and thus leaf area, leaf biomass, and potential

photosynthesis," they went on to suggest that the increases in plant growth and vitality implied by their NDVI data were primarily driven by concurrent increases in near-surface air temperature, although temperatures may have actually declined throughout the eastern part of the United States over the period of their study.

After lying dormant for about a year, Zhou *et al.*'s attribution of this "greening" of the continent to concurrent increases in near-surface air temperature was challenged by Ahlbeck (2002), who suggested that the observed upward trend in NDVI was primarily driven by the concurrent increase in the air's CO<sub>2</sub> concentration, and that fluctuations in temperature were primarily responsible for variations about the more steady upward trend defined by the increase in CO<sub>2</sub>. In replying to this challenge, Kaufmann *et al.* (2002) claimed Ahlbeck was wrong and reaffirmed their initial take on the issue. In a further analysis of the question, in our editorial of [18 Sep 2002](#), *CO<sub>2</sub> Science* concluded that it was Ahlbeck who was "clearly the 'more correct' of the two camps." In fact, they came to the conclusion he was actually *totally* correct.

About the same time, Hicke *et al.* (2002) computed net primary productivity (NPP) over North America for the years 1982-1998 using the Carnegie-Ames-Stanford Approach (CASA) carbon cycle model, which was driven by a satellite NDVI record at 8-km spatial resolution. This effort revealed that NPP increases of 30% or more occurred across the continent from 1982 to 1998. During this period, the air's CO<sub>2</sub> concentration rose by 25.74 ppm, as calculated from the Mauna Loa data of Keeling and Whorf (1998), which amount is 8.58% of the 300 ppm increase that is often used as a reference for expressing plant growth responses to atmospheric CO<sub>2</sub> enrichment. Consequently, for herbaceous plants that display NPP increases of 30-40% in response to a 300-ppm increase in atmospheric CO<sub>2</sub> concentration, the CO<sub>2</sub>-induced NPP increase experienced between 1982 and 1998 would be expected to have been 2.6-3.4%. Similarly, for woody plants that display NPP increases of 60-80% in response to a 300-ppm increase in atmospheric CO<sub>2</sub> (Saxe *et al.*, 1998; Idso and Kimball, 2001), the expected increase in productivity between 1982 and 1998 would have been 5.1-6.9%. Since both of these NPP increases are considerably less than the 30% or more observed by Hicke *et al.*, additional factors must have helped to stimulate NPP over this period, some of which may have been concomitant increases in precipitation and air temperature, the tendency for warming to lengthen growing seasons and enhance the aerial fertilization effect of rising CO<sub>2</sub> concentrations, increasingly intensive crop and forest management, increasing use of genetically improved plants, the regrowth of forests on abandoned cropland, and improvements in agricultural practices such as irrigation and fertilization. Whatever the mix might have been, one thing is clear: its ultimate effect was *overwhelming positive*.

In a vastly different type of study based on a 48-year record derived from an average of 17 measurements per year Raymond and Cole (2003) demonstrated that the export of *alkalinity*, in the form of bicarbonate ions, from the USA's Mississippi River to the Gulf of Mexico had increased by approximately 60% since 1953. "This increased export," as they described it, was "in part the result of increased flow resulting from higher rainfall in the Mississippi basin," which had led to a 40% increase in annual Mississippi River discharge to the Gulf of Mexico over

the same time period. The remainder, however, had to have been due to increased rates of chemical weathering of soil minerals.

What factors might have been responsible for this phenomenon? The two researchers noted that potential mechanisms included "an increase in atmospheric CO<sub>2</sub>, an increase [in] rainwater throughput, or an increase in plant and microbial production of CO<sub>2</sub> and organic acids in soils due to biological responses to increased rainfall and temperature." Unfortunately, they forgot to mention the increase in terrestrial plant productivity that is produced by the increase in the aerial fertilization effect provided by the historical rise in the air's CO<sub>2</sub> content, which also leads to "an increase in plant and microbial production of CO<sub>2</sub> and organic acids in soils." And as we note in our review of their paper, this phenomenon should have led to an increase in Mississippi River alkalinity equivalent to that which they had observed since 1953.

In a still-different type of study, using data obtained from dominant stands of loblolly pine plantations growing at 94 locations spread across the southeastern United States, Westfall and Amateis (2003) employed mean height measurements made at three-year intervals over a period of 15 years to calculate a *site index* related to the mean growth rate for each of the five three-year periods, which index would be expected to increase monotonically if growth rates were being enhanced above normal by some monotonically-increasing factor that promotes growth. This work revealed, in their words, that "mean site index over the 94 plots consistently increased at each remeasurement period," which would suggest, as they further state, that "loblolly pine plantations are realizing greater than expected growth rates," and, we would add, that the growth rate increases are growing larger and larger with each succeeding three-year period.

As to what could be causing the monotonically increasing growth rates of loblolly pine trees over the entire southeastern United States, Westfall and Amateis named increases in temperature and precipitation in addition to rising atmospheric CO<sub>2</sub> concentrations. However, they report that a review of annual precipitation amounts and mean ground surface temperatures showed no trends in these factors over the period of their study. They also suggested that if increased nitrogen deposition were the cause, "such a factor would have to be acting on a regional scale to produce growth increases over the range of study plots." Hence, they tended to favor the ever-increasing aerial fertilization effect of atmospheric CO<sub>2</sub> enrichment as being responsible for the accelerating pine tree growth rates.

Returning to satellite studies, Lim *et al.* (2004) correlated the monthly rate of relative change in NDVI, which they derived from advanced very high resolution radiometer data, with the rate of change in atmospheric CO<sub>2</sub> concentration during the natural vegetation growing season within three different eco-region zones of North America (Arctic and Sub-Arctic Zone, Humid Temperate Zone, and Dry and Desert Zone, which they further subdivided into 17 regions) over the period 1982-1992, after which they explored the temporal progression of annual minimum NDVI over the period 1982-2001 throughout the eastern humid temperate zone of North America. The result of these operations was that in all of the regions but one, according to the researchers, " $\delta\text{CO}_2$  was positively correlated with the rate of change in vegetation greenness in

the following month, and most correlations were high," which they say is "consistent with a CO<sub>2</sub> fertilization effect" of the type observed in "experimental manipulations of atmospheric CO<sub>2</sub> that report a stimulation of photosynthesis and above-ground productivity at high CO<sub>2</sub>." In addition, they determined that the yearly "minimum vegetation greenness increased over the period 1982-2001 for all the regions of the eastern humid temperate zone in North America."

As for the cause of this phenomenon, Lim *et al.* say that rising CO<sub>2</sub> could "increase minimum greenness by stimulating photosynthesis at the beginning of the growing season," citing the work of Idso *et al.* (2000), who discovered that although new spring branch growth of sour orange trees began on exactly the same day of the year in both ambient (400 ppm) and CO<sub>2</sub>-enriched (700 ppm) open-top chambers, the *rate* of new-branch growth was initially *vastly* greater in the CO<sub>2</sub>-enriched trees. Three weeks after branch growth began in the spring, for example, new branches on the CO<sub>2</sub>-enriched trees were typically more than *four times* more massive than their counterparts on the ambient-treatment trees; while on a per-tree basis, over *six times* more new-branch biomass was produced on the CO<sub>2</sub>-enriched trees, before declining to an approximate 80% stimulation typical of the bulk of the growing season. Consequently, by looking for a manifestation of the CO<sub>2</sub> fertilization effect at the time of year it is apt to be most strongly expressed, Lim *et al.* may well have found it. Between 1982 and 2001, for example, the air's CO<sub>2</sub> concentration rose by approximately 30 ppm. From Idso *et al.*'s findings of (1) more than a 300% initial increase in the biomass of new sour orange tree branches for a 300-ppm increase in the air's CO<sub>2</sub> concentration and (2) more than a 500% initial increase in *per-tree* new-branch biomass, we calculate that yearly minimum greenness should have increased by something between *something just over 30%* and *something just over 50%*, if other woody plants respond to atmospheric CO<sub>2</sub> enrichment as sour orange trees do; and when we calculate the mean 19-year increase in NDVI for the seven regions for which Lim *et al.* present data, we get an increase of *something just over 40%*, indicative of the fact that Lim *et al.*'s data are not only *qualitatively* consistent with their hypothesis, they are right on the mark *quantitatively* as well.

In a somewhat similar study, but one that focused more intensely on *climate* change, Xiao and Moody (2004) examined the responses of the normalized difference vegetation index integrated over the growing season (gNDVI) to annual and seasonal precipitation, maximum temperature (Tmax) and minimum temperature (Tmin) over an 11-year period (1990-2000) for six biomes in the conterminous United States (Evergreen Needleleaf Forest, Deciduous Broadleaf Forest, Mixed Forest, Open Shrubland, Woody Savanna and Grassland), focusing on within- and across-biome variance in long-term average gNDVI and emphasizing the degree to which this variance is explained by spatial gradients in long-term average seasonal climate. The results of these protocols indicated that the greatest positive climate-change impacts on biome productivity were caused by increases in spring, winter and fall precipitation, as well as increases in fall and spring temperature, especially Tmin, which has historically increased at roughly twice the rate of Tmax in the United States. Hence, "if historical climatic trends and the biotic responses suggested in this analysis continue to hold true," in the words of Xiao and Moody, "we can anticipate further increases in productivity for both forested and nonforested

ecoregions in the conterminous US, with associated implications for carbon budgets and woody proliferation," which once again spells good news for the biosphere.

Jumping a couple years closer to the present, Goetz *et al.* (2005) transformed satellite-derived NDVI data obtained across boreal North America (Canada and Alaska) for the period 1982-2003 into photosynthetically-active radiation absorbed by green vegetation and treated the result as a proxy for relative June-August gross photosynthesis (Pg), stratifying the results by vegetation type and comparing them with spatially-matched concomitant trends in surface air temperature data. Over the course of the study, this work revealed that area-wide tundra experienced a significant increase in Pg in response to a similar increase in air temperature; and Goetz *et al.* say "this observation is supported by a wide and increasing range of local field measurements characterizing elevated net CO<sub>2</sub> uptake (Oechel *et al.*, 2000), greater depths of seasonal thaw (Goulden *et al.*, 1998), changes in the composition and density of herbaceous vegetation (Chapin *et al.*, 2000; Epstein *et al.*, 2004), and increased woody encroachment in the tundra areas of North America (Sturm *et al.*, 2001)." In the case of interior forest, on the other hand, there was no significant increase in air temperature and essentially no change in Pg, with the last data point of the series being essentially indistinguishable from the first. This latter seemingly aberrant observation is in harmony with the fact that at low temperatures the growth-promoting effects of increasing atmospheric CO<sub>2</sub> levels are often very small or even non-existent (Idso and Idso, 1994), which is what appears to have been the case with North American boreal forests over the same time period. As a result, Canada's and Alaska's tundra ecosystems exhibited increasing productivity over the past couple of decades, while their boreal forests did not.

Also working in Alaska, Tape *et al.* (2006) analyzed *repeat photography* data from a photo study of the Colville River conducted between 1945 and 1953, as well as 202 new photos of the same sites that were obtained between 1999 and 2002, to determine the nature of shrub expansion in that region over the past half-century. This approach revealed, in their words, that "large shrubs have increased in size and abundance over the past 50 years, colonizing areas where previously there were no large shrubs." In addition, they say their review of plot and remote sensing studies confirms that "shrubs in Alaska have expanded their range and grown in size" and that "a population of smaller, intertussock shrubs not generally sampled by the repeat photography, is also expanding and growing." Taken together, they conclude that "these three lines of evidence allow us to infer a general increase in tundra shrubs across northern Alaska." So what is the cause of the shrub expansion? ... and when did it begin?

Tape *et al.* are inclined to attribute it to large-scale pan-Arctic warming; and from analyses of logistic growth curves, they estimate that the expansion began about 1900, "well before the current warming in Alaska (which started about 1970)." Hence, they conclude that "the expansion predates the most recent warming trend and is perhaps associated with the general warming since the Little Ice Age." These inferences appear reasonable, although we would add that the 80-ppm increase in the atmosphere's CO<sub>2</sub> concentration since 1900 likely played a role in the shrub expansion as well. If continued, the researchers say the transition "will alter the



fundamental architecture and function of this ecosystem with important ramifications," the great bulk of which, in our opinion, will be positive, as *the greening of the earth continues*.

Working at eight different sites within the Pacific Northwest of the United States, Soule and Knapp (2006) studied ponderosa pine trees to see how they may have responded to the increase in the atmosphere's CO<sub>2</sub> concentration that occurred after 1950. The two geographers say the sites they chose "fit several criteria designed to limit potential confounding influences associated with anthropogenic disturbance." In addition, they selected locations with "a variety of climatic and topo-edaphic conditions, ranging from extremely water-limiting environments ... to areas where soil moisture should be a limiting factor for growth only during extreme drought years." They also say that all sites were located in areas "where ozone concentrations and nitrogen deposition are typically low."

At all eight of the sites that met all of these criteria, Soule and Knapp obtained core samples from about 40 mature trees that included "the potentially oldest trees on each site," so that their results would indicate, as they put it, "the response of mature, naturally occurring ponderosa pine trees that germinated before anthropogenically elevated CO<sub>2</sub> levels, but where growth, particularly post-1950, has occurred under increasing and substantially higher atmospheric CO<sub>2</sub> concentrations." Utilizing meteorological evaluations of the Palmer Drought Severity Index, they thus compared ponderosa pine radial growth rates during matched wet and dry years pre- and post-1950.

So what did they find? Overall, the two researchers discovered a post-1950 radial growth enhancement that was "more pronounced during drought years compared with wet years, and the greatest response occurred at the most stressed site." As for the magnitude of the response, they determined that "the relative change in growth [was] upward at seven of our [eight] sites, ranging from 11 to 133%."

With respect to the significance of their observations, Soule and Knapp say their results show that "radial growth has increased in the post-1950s period ... while climatic conditions have generally been unchanged," which further suggests that "nonclimatic driving forces are operative." In addition, they say the "radial growth responses are generally consistent with what has been shown in long-term open-top chamber (Idso and Kimball, 2001) and FACE studies (Ainsworth and Long, 2005)." Hence, they conclude their findings "suggest that elevated levels of atmospheric CO<sub>2</sub> are acting as a driving force for increased radial growth of ponderosa pine, but that the overall influence of this effect may be enhanced, reduced or obviated by site-specific conditions."

Summarizing their findings, Soule and Knapp recount how they had "hypothesized that ponderosa pine ... would respond to gradual increases in atmospheric CO<sub>2</sub> over the past 50 years, and that these effects would be most apparent during drought stress and on environmentally harsh sites," and in the following sentence they say their results "support these hypotheses." Hence, they conclude their paper by stating that "an atmospheric CO<sub>2</sub>-driven growth-enhancement effect exists for ponderosa pine growing under specific natural

conditions within the interior Pacific Northwest," providing yet another important example of the ongoing CO<sub>2</sub>-induced *greening of the earth*.

Last of all, and most recently, we come to the study of Wang *et al.* (2006), who examined ring-width development in cohorts of young and old white spruce trees in a mixed grass-prairie ecosystem in southwestern Manitoba, Canada, where a 1997 wildfire killed most of the older trees growing in high-density *spruce islands*, but where younger trees slightly removed from the islands escaped the ravages of the flames. There, "within each of a total of 24 burned islands," in the words of the three researchers, "the largest dominant tree (dead) was cut down and a disc was then sampled from the stump height," while "adjacent to each sampled island, a smaller, younger tree (live) was also cut down, and a disc was sampled from the stump height." After removing size-, age- and climate-related trends in radial growth from the ring-width histories of the trees, Wang *et al.* plotted the residuals as functions of time for the 30-year periods for which both the old and young trees would have been approximately the same age: 1900-1929 for the old trees and 1970-1999 for the young trees. During the first of these periods, the atmosphere's CO<sub>2</sub> concentration averaged 299 ppm; during the second it averaged 346 ppm. Also, the mean rate-of-rise of the atmosphere's CO<sub>2</sub> concentration was 0.37 ppm/year for first period and 1.43 ppm/year for the second.

The results of this exercise revealed that the slope of the linear regression describing the rate-of-growth of the ring-width residuals for the later period (when the air's CO<sub>2</sub> concentration was 15% greater and its rate-of-rise 285% greater) was more than *twice* that of the linear regression describing the rate-of-growth of the ring-width residuals during the earlier period. As the researchers describe it, these results show that "at the same developmental stage, a greater growth response occurred in the late period when atmospheric CO<sub>2</sub> concentration and the rate of atmospheric CO<sub>2</sub> increase were both relatively high," and they say that "these results are consistent with expectations for CO<sub>2</sub>-fertilization effects." In fact, they say "the response of the studied young trees can be taken as strong circumstantial evidence for the atmospheric CO<sub>2</sub>-fertilization effect."

Another thing Wang *et al.* learned was that "postdrought growth response was much stronger for young trees (1970-1999) compared with old trees at the same development stage (1900-1929)," and they add that "higher atmospheric CO<sub>2</sub> concentration in the period from 1970-1999 may have helped white spruce recover from severe drought." In a similar vein, they also determined that young trees showed a weaker relationship to precipitation than did old trees, noting that "more CO<sub>2</sub> would lead to greater water-use efficiency, which may be dampening the precipitation signal in young trees."

In summary, Wang *et al.*'s unique study provides an exciting real-world example of the tremendous benefits the historical increase in the air's CO<sub>2</sub> content has likely conferred on nearly all of earth's plants, and especially its long-lived woody species. Together with the results of the other North American studies we have reviewed, this body of research thus paints a picture of the planet's terrestrial vegetation that is just the *opposite* of what is promulgated by the world's climate alarmists. Land-based plants are *not* "headed to hell in a hand basket." They

are *thriving*, thanks in large part to the ongoing rise in the atmosphere's CO<sub>2</sub> concentration - *as well as global warming!* - as ever more real-world observations continue to demonstrate.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/g/namergreen.php>.

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### 6.8.5. Global

How have earth's terrestrial plants responded - on average and in their entirety - to the atmospheric temperature and CO<sub>2</sub> increases of the past quarter-century? In this subsection we report the results of studies that have looked at either the world as a whole or groups of more than two continents at the same time.

In one of the earlier studies of the subject that we reviewed on our website, Joos and Bruno (1998) used ice core and direct observations of atmospheric CO<sub>2</sub> and <sup>13</sup>C to reconstruct the histories of terrestrial and oceanic uptake of anthropogenic carbon over the past two centuries. This project revealed, in their words, that "the biosphere acted on average as a source [of CO<sub>2</sub>] during the last century and the first decades of this century ... Then, the biosphere turned into a [CO<sub>2</sub>] sink," which implies a significant increase in global vegetative productivity over the last half of the 20th century.

More recently, Cao *et al.* (2004) derived net primary production (NPP) values at 8-km and 10-day resolutions for the period 1981-2000 using variables based almost entirely on satellite observations, as described in the Global Production Efficiency Model (GLO-PEM), which consists, in their words, "of linked components that describe the processes of canopy radiation absorption, utilization, autotrophic respiration, and the regulation of these processes by environmental factors (Prince and Goward, 1995; Goetz *et al.*, 2000)." In following this procedure, they learned that over the last two decades of the 20th century, *when the heat was on*, "there was an increasing trend toward enhanced terrestrial NPP," which they say was "caused mainly by increases in atmospheric carbon dioxide and precipitation."

A year later, Cao *et al.* (2005) used the CEVSA (Carbon Exchanges in the Vegetation-Soil-Atmosphere system) model (Cao and Woodward, 1998; Cao *et al.*, 2002), forced by observed variations in climate and atmospheric CO<sub>2</sub>, to quantify changes in NPP, soil heterotrophic respiration (HR) and net ecosystem production (NEP) from 1981 to 1998. As an independent check on the NPP estimate of CEVSA, they also estimated 10-day NPP from 1981-2000 with the GLO-PEM model that uses data almost entirely from remote sensing, including both the normalized difference vegetation index (NDVI) and meteorological variables (Prince and Goward, 1995; Cao *et al.*, 2004). This protocol revealed, in Cao *et al.*'s words, that "global terrestrial temperature increased by 0.21°C from the 1980s to the 1990s, and this alone increased HR more than NPP and hence reduced global annual NEP." *However*, they found that "combined changes in temperature and precipitation increased global NEP significantly," and

that "increases in atmospheric CO<sub>2</sub> produced further increases in NPP and NEP." They also discovered that "the CO<sub>2</sub> fertilization effect [was] particularly strong in the tropics, compensating for the negative effect of warming on NPP." Enlarging on this point, they write that "the response of photosynthetic biochemical reactions to increases in atmospheric CO<sub>2</sub> is greater in warmer conditions, so the CO<sub>2</sub> fertilization effect will increase with warming in cool regions and be high in warm environments." The end result of the application of these models and measurements was their finding that global NEP increased "from 0.25 Pg C yr<sup>-1</sup> in the 1980s to 1.36 Pg C yr<sup>-1</sup> in the 1990s."

Commenting on their findings, Cao *et al.* note that "the NEP that was induced by CO<sub>2</sub> fertilization and climatic variation accounted for 30% of the total terrestrial carbon sink implied by the atmospheric carbon budget (Schimel *et al.*, 2001), and the fraction changed from 13% in the 1980s to 49% in the 1990s," which indicates the growing importance of the CO<sub>2</sub> fertilization effect. Also, they say that "the increase in the terrestrial carbon sink from the 1980s to the 1990s was a continuation of the trend since the middle of the twentieth century, rather than merely a consequence of short-term climate variability," which suggests that as long as the air's CO<sub>2</sub> content continues its upward course, so too will its stimulation of the terrestrial biosphere likely continue its upward course.

Using a newly-developed satellite-based vegetation index (Version 3 Pathfinder NDVI) in conjunction with a gridded global climate dataset (global monthly mean temperature and precipitation at 0.5° resolution from New *et al.*, 2000), Xiao and Moody (2005) analyzed trends in global vegetative activity from 1982 to 1998. The greening trends they found exhibited substantial latitudinal and longitudinal variability, with the most intense greening of the globe located in high northern latitudes, portions of the tropics, southeastern North America and eastern China. Temperature was found to correlate strongly with greening trends in Europe, eastern Eurasia and tropical Africa. Precipitation, on the other hand, was *not* found to be a significant driver of increases in greenness, except for isolated and spatially fragmented regions. Some decreases in greenness were also observed, mainly in the Southern Hemisphere in southern Africa, southern South America and central Australia, which trends were associated with concomitant increases in temperature and decreases in precipitation. There were also large regions of the globe that showed no trend in greenness over the 17-year period, as well as large areas that underwent strong greening that showed no association with trends of either temperature or precipitation. These greening trends, as they concluded, must have been the result of other factors, such as "CO<sub>2</sub> fertilization, reforestation, forest regrowth, woody plant proliferation and trends in agricultural practices," about which others will have more to say as we continue.

Working with satellite observations of vegetative activity over the period 1982 to 1999, Nemani *et al.* (2003) discovered that the productivity of earth's terrestrial vegetation rose significantly over this period. More specifically, they determined that terrestrial net primary production (NPP) increased by 6.17%, or 3.42 PgC, over the 18 years between 1982 and 1999. What is more, they observed net positive responses over all latitude bands studied: 4.2% (47.5-22.5°S), 7.4% (22.5°S-22.5°N), 3.7% (22.5-47.5°N), and 6.6% (47.5-90.0°N).

The eight researchers mention a number of likely contributing factors to these significant NPP increases: nitrogen deposition and forest regrowth in northern mid and high latitudes, wetter rainfall regimes in water-limited regions of Australia, Africa, and the Indian subcontinent, increased solar radiation reception over radiation-limited parts of Western Europe and the equatorial tropics, warming in many parts of the world, and the aerial fertilization effect of rising atmospheric CO<sub>2</sub> concentrations *everywhere*.

With respect to the latter factor, which is featured prominently on our website, Nemani *et al.* say that "an increase in NPP of only 0.2% per 1-ppm increase in CO<sub>2</sub> could explain all of the estimated global NPP increase of 6.17% over 18 years *and is within the range of experimental evidence* [our italics]." However, they report that terrestrial NPP increased by more than 1% per year in Amazonia alone, noting that "this result cannot be explained solely by CO<sub>2</sub> fertilization." We tend to agree with Nemani *et al.* on this point, but also note that the aerial fertilization effect of atmospheric CO<sub>2</sub> enrichment is most pronounced at higher temperatures (see the previous section Growth Response to CO<sub>2</sub> with Other Variables - Temperature in this report), rising from next to nothing at a mean temperature of 10°C to a 0.33% NPP increase per 1-ppm increase in CO<sub>2</sub> at a mean temperature of 36°C for a mixture of plants comprised predominantly of herbaceous species (Idso and Idso, 1994). For woody plants, we could possibly expect this number to be two (Idso, 1999) or even three (Saxe *et al.*, 1998; Idso and Kimball, 2001; Leavitt *et al.*, 2003) times larger, yielding a 0.7% to 1% NPP increase per 1-ppm increase in atmospheric CO<sub>2</sub>, which would represent the lion's share of the growth stimulation observed by Nemani *et al.* in tropical Amazonia.

Be that as it may, the important take-home message of Nemani *et al.*'s study is that satellite-derived observations indicate that the planet's terrestrial vegetation significantly increased its productivity over the last two decades of the 20th century, in the face of a host of both real and imagined environmental stresses, chief among the latter of which was what climate alarmists routinely claim to be *unprecedented CO<sub>2</sub>-induced global warming*, which they routinely represent as being anathema to life on earth. However, the doomsayers are 180 degrees out of phase with reality in this contention, as earth's vegetation has spoken *loud and clear* - by its ever-increasing growth rate - that it actually *loves* higher air temperatures and atmospheric CO<sub>2</sub> concentrations.

In another approach to the subject, Idso (1995) laid out the evidence for a worldwide increase in the growth rates of earth's forests that has been coeval with the progression of the Industrial Revolution and the rising CO<sub>2</sub> content of the atmosphere. The development of this concept *began* with the study of LaMarche *et al.* (1984), who analyzed annual growth rings of two species of pine tree growing near the timberline in California, Colorado, Nevada and New Mexico (USA), and who thereby discovered large increases in growth rate between 1859 and 1983, which rates exceeded what might have been expected from climatic trends but were consistent with the global trend of atmospheric CO<sub>2</sub>. The developmental journey then *continued* with a study of ring-width measurements of Douglas fir trees in British Columbia, Canada, that also revealed a marked increase in growth in the trees' latter decades (Parker *et*

*al.*, 1987), leading the principal investigator of the project to state that "environmental influences other than increased CO<sub>2</sub> have not been found that would explain this [phenomenon]." West (1988) reported much the same thing with respect to long-leaf pines in Georgia, i.e., that their annual growth increments had begun to rise at an unusual rate about 1920, increasing by approximately 30% by the mid-1980s; and he too stated that "the increased growth cannot be explained by trends in precipitation, temperature, or Palmer Drought Severity Index," leaving the rising CO<sub>2</sub> content of the atmosphere as the likely cause of the increase in productivity.

Contemporaneously, stands of Scots pines in northern Finland were found to have experienced growth increases ranging from 15 to 43% between 1950 and 1983 (Hari *et al.*, 1984; Hari and Arovaara, 1988). As to the cause of this phenomenon, the researchers stated that "CO<sub>2</sub> seems to be the only environmental factor that has been changing systematically during this century in the remote area under study," and it was thus to this factor that they looked for an explanation of their observations.

The next major development in the *continuing saga* was the finding of Graybill and Idso (1993) that very long ring-width chronologies (some stretching back nearly 1800 years) of high-altitude long-lived bristlecone, foxtail and limber pine trees in Arizona, California, Colorado and Nevada (USA) all developed an unprecedented upward growth trend somewhere in the 1850s that continued as far towards the present as the records extended. In this case, too, like the ones that preceded it, comparisons of the chronologies with temperature and precipitation records ruled out the possibility that either of these climatic variables played a significant role in enhancing the trees' growth rates, strongly implicating the historical rise in the air's CO<sub>2</sub> content as the factor responsible for their ever-increasing productivity over the prior century and a half.

Perhaps the most striking evidence of all for the significant 20th-century growth enhancement of earth's forests by the historical increase in the air's CO<sub>2</sub> concentration was provided by the study of Phillips and Gentry (1994). Noting that turnover rates of mature tropical forests correlate well with measures of net productivity (Weaver and Murphy, 1990), the two scientists assessed the turnover rates of 40 tropical forests from around the world in order to test the hypothesis that global forest productivity was increasing *in situ*. In doing so, they found that the turnover rates of these highly productive forests had indeed been rising ever higher since at least 1960, with an apparent pan-tropical acceleration since 1980. In discussing what might be causing this phenomenon, they stated that "the accelerating increase in turnover coincides with an accelerating buildup of CO<sub>2</sub>," and as Pimm and Sugden (1994) stated in a companion article, it was "the consistency and simultaneity of the changes on several continents that lead Phillips and Gentry to their conclusion that enhanced productivity induced by increased CO<sub>2</sub> is the most plausible candidate for the cause of the increased turnover."

Four years later, a group of eleven researchers headed by Phillips (Phillips *et al.*, 1998) reported another impressive finding. Working with data on tree basal area (a surrogate for tropical forest biomass) for the period 1958-1996, which they obtained from *several hundred* plots of mature



tropical trees scattered about the world, they found that average forest biomass for the tropics as a whole had increased substantially. In fact, they calculated that the increase amounted to approximately 40% of the missing terrestrial carbon sink of the entire globe. Hence, they suggested that "intact forests may be helping to buffer the rate of increase in atmospheric CO<sub>2</sub>, thereby reducing the impacts of global climate change," as Idso (1991a,b) had earlier suggested, and they identified the aerial fertilization effect of the ongoing rise in the air's CO<sub>2</sub> content as one of the factors responsible for this phenomenon. Other contemporary studies also supported their findings (Grace *et al.*, 1995; Malhi *et al.*, 1998), verifying the fact that neotropical forests were indeed accumulating ever more carbon; and Phillips *et al.* (2002) continued to state that this phenomenon was occurring "possibly in response to the increasing atmospheric concentrations of carbon dioxide (Prentice *et al.*, 2001; Malhi and Grace, 2000)."

As time progressed, however, it became less and less popular (i.e., ever more *politically incorrect*) to report positive biological consequences of the ongoing rise in the air's CO<sub>2</sub> concentration; and the conclusions of Phillips and company began to be repeatedly challenged (Sheil, 1995; Sheil and May, 1996; Condit, 1997; Clark, 2002; Clark *et al.*, 2003). In response to those challenges, *CO<sub>2</sub> Science* published an editorial rebuttal ([18 Jun 2003](#)), after which Phillips, joined by 17 other researchers (Lewis *et al.*, 2005b), *including one who had earlier criticized his and his colleagues' conclusions*, published a new analysis that vindicated Phillips *et al.*'s earlier thoughts on the subject.

One of the primary concerns of the critics of Phillips *et al.*'s work was that their meta-analyses included sites with a wide range of tree census intervals (2-38 years), which they claimed could be confounding or "perhaps even driving conclusions from comparative studies," as Lewis *et al.* (2005b) describe it. However, in Lewis *et al.*'s detailed study of this potential problem, which they concluded was indeed real, they found that re-analysis of Phillips *et al.*'s published results "shows that the pan-tropical increase in stem turnover rates over the late 20th century cannot be attributed to combining data with differing census intervals." Or as they state more obtusely in another place, "the conclusion that turnover rates have increased in tropical forests over the late 20th century is robust to the charge that this is an artifact due to the combination of data that vary in census interval (cf. Sheil, 1995)."

Lewis *et al.* (2005b) additionally noted that "Sheil's (1995) original critique of the evidence for increasing turnover over the late 20th century also suggests that the apparent increase could be explained by a single event, the 1982-83 El Niño Southern Oscillation (ENSO), as many of the recent data spanned this event." However, as they continued, "recent analyses from Amazonia have shown that growth, recruitment and mortality rates have simultaneously increased within the same plots over the 1980s and 1990s, as has net above-ground biomass, both in areas largely unaffected, and in those strongly affected, by ENSO events (Baker *et al.*, 2004; Lewis *et al.*, 2004a; Phillips *et al.*, 2004)."

In a *satellite* study of the world's tropical forests, Ichii *et al.* (2005) "simulated and analyzed 1982-1999 Amazonian, African, and Asian carbon fluxes using the Biome-BGC prognostic carbon cycle model driven by National Centers for Environmental Prediction reanalysis daily climate

data," after which they "calculated trends in gross primary productivity (GPP) and net primary productivity (NPP)." This work revealed that solar radiation variability was the primary factor responsible for interannual *variations* in GPP, followed by temperature and precipitation variability, while in terms of GPP trends, Ichii *et al.* report that "recent changes in atmospheric CO<sub>2</sub> and climate promoted terrestrial GPP increases with a significant linear trend in all three tropical regions." In the Amazonian region, the rate of GPP increase was 0.67 PgC year<sup>-1</sup> decade<sup>-1</sup>, while in Africa and Asia it was about 0.3 PgC year<sup>-1</sup> decade<sup>-1</sup>. Likewise, they report that "CO<sub>2</sub> fertilization effects strongly increased recent NPP trends in regional totals."

In a review of these several global forest studies, as well as many others (which led to their citing 186 scientific journal articles), Boisvenue and Running (2006) examined reams of "documented evidence of the impacts of climate change trends on forest productivity since the middle of the 20th century." In doing so, they found that "globally, based on both satellite and ground-based data, climatic changes seemed to have a generally positive impact on forest productivity when water was not limiting," which was most of the time, because they report that "less than 7% of forests are in strongly water-limited systems." Hence, and in spite of what climate alarmists routinely describe as *unprecedented increases* in the "twin evils" of rising atmospheric CO<sub>2</sub> concentrations and air temperatures (which some have described as being greater threats to the world than global terrorism or nuclear warfare), there has *in fact* been what Boisvenue and Running call a significant "greening of the biosphere," and the world's forests in particular.

Last of all, in one final satellite study of the globe, Young and Harris (2005) analyzed, for the majority of earth's land surface, a near 20-year time series (1982-1999) of NDVI data, based on measurements obtained from the Advanced Very High Resolution Radiometer (AVHRR) carried aboard U.S. National Oceanic and Atmospheric Administration satellites. In doing so, they employed two different datasets derived from the sensor: the Pathfinder AVHRR Land (PAL) data set and the Global Inventory Modeling and Mapping Studies (GIMMS) dataset. Based on their analysis of the PAL data, the two researchers determined that "globally more than 30% of land pixels increased in annual average NDVI greater than 4% and more than 16% persistently increased greater than 4%," while "during the same period less than 2% of land pixels declined in NDVI and less than 1% persistently declined." With respect to the GIMMS dataset, they report that "even more areas were found to be persistently increasing (greater than 20%) and persistently decreasing (more than 3%)." All in all, they report that "between 1982 and 1999 the general trend of vegetation change throughout the world has been one of increasing photosynthesis."

As for what has been *responsible* for the worldwide increase in photosynthesis - which is the ultimate food source for nearly all of the biosphere - the researchers mention global warming (perhaps it's not so bad after all), as well as "associated precipitation change and increases in atmospheric carbon dioxide," citing Myneni *et al.* (1997) and Ichii *et al.* (2002). In addition, they say that "many of the areas of decreasing NDVI are the result of human activity," primarily deforestation (Skole and Tucker, 1993; Steininger *et al.*, 2001) and urbanization Seto *et al.* (2000).

In conclusion, the results of these many studies demonstrate there has been an increase in plant growth rates throughout the world since the inception of the Industrial Revolution, and that this phenomenon has been gradually accelerating over the years, in concert with the historical increases in the air's CO<sub>2</sub> content and its temperature.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/g/greeningearth.php>.

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## 7. CARBON SEQUESTRATION

Additional information on this topic, including reviews not discussed here, can be found at [http://www.co2science.org/subject/c/subject\\_c.php](http://www.co2science.org/subject/c/subject_c.php) under the heading Carbon Sequestration.

### 7.1. Decomposition

#### 7.1.1. Processes and Properties

Atmospheric CO<sub>2</sub> enrichment stimulates photosynthesis and growth in nearly all plants, typically producing more non-structural carbohydrates, which can be used to manufacture more carbon-based secondary compounds (CBSCs) or *phenolics*. This observation is important because phenolics tend to inhibit the decomposition of the organic matter in which they are found (Freeman *et al.*, 2001). Hence, if elevated levels of atmospheric CO<sub>2</sub> lead to the production of more of these decay-resistant substances, one would expect the ongoing rise in the air's CO<sub>2</sub> content to lead to the enhanced sequestration of plant-litter-derived carbon in the world's soils, producing a negative feedback phenomenon that would tend to slow the rate of rise of the air's CO<sub>2</sub> content and thereby moderate CO<sub>2</sub>-induced global warming. So what do experiments reveal about this hypothesis?

For a long time the picture was rather muddled. Many studies reported the expected increases in CBSC concentrations with experimentally-created increases in the air's CO<sub>2</sub> content. Others, however, could find no significant plant phenolic content changes; while a few even detected CO<sub>2</sub>-induced *decreases* in CBSC concentrations. Although chaos thus reigned in this area for some time, Penuelas *et al.* (1997) finally brought order to the issue when they identified the key role played by soil nitrogen.

In analyzing the results of several different studies, Penuelas *et al.* noticed that when soil nitrogen supply was less than adequate, some of the CBSC responses to a doubling of the air's CO<sub>2</sub> content were negative, i.e., a portion of the studies indicated that plant CBSC concentrations actually declined as the air's CO<sub>2</sub> content rose. When soil nutrient supply was more than adequate, however, the responses were almost all positive, with plant CBSC concentrations rising in response to a doubling of the air's CO<sub>2</sub> concentration. In addition, when the CO<sub>2</sub> content of the air was tripled, *all* CBSC responses, under both low and high soil nitrogen conditions, were positive.

The solution to the puzzle was thus fairly simple. With a tripling of the air's CO<sub>2</sub> content, nearly all plants exhibited increases in CBSC production; but with only a doubling of the atmospheric CO<sub>2</sub> concentration, adequate nitrogen was needed to ensure a positive CBSC response.

What makes these observations especially exciting is that atmospheric CO<sub>2</sub> enrichment, in addition to enhancing plant growth, typically stimulates nitrogen fixation in both woody (Olesniewicz and Thomas, 1999) and non-woody (Niklaus *et al.*, 1998; Dakora and Drake, 2000) legumes. Hence, as the air's CO<sub>2</sub> content continues to rise, earth's nitrogen-fixing plants should



become ever more proficient in this important enterprise. In addition, some of the extra nitrogen thus introduced into earth's ecosystems will likely be shared with non-nitrogen-fixing plants. Also, since the microorganisms responsible for nitrogen fixation are found in nearly all natural ecosystems (Gifford, 1992), and since atmospheric CO<sub>2</sub> enrichment can directly stimulate the nitrogen-fixing activities of these microbes (Lowe and Evans, 1962), it can be appreciated that the ongoing rise in the air's CO<sub>2</sub> content will likely provide more nitrogen for the production of more CBSCs in *all* of earth's plants. And with ever-increasing concentrations of decay-resistant materials being found throughout plant tissues, the plant-derived organic matter that is incorporated into soils should remain there for ever longer periods of time.

On the other hand, in a meta-analysis of the effects of atmospheric CO<sub>2</sub> enrichment on leaf-litter chemistry and decomposition rate that was based on a total of 67 experimental observations, Norby *et al.* (2001) found that elevated atmospheric CO<sub>2</sub> concentrations - mostly between 600 and 700 ppm - reduced leaf-litter nitrogen concentration by about 7%. But in experiments where plants were grown under as close to natural conditions as possible, such as in open-top chambers, FACE plots, or in the proximity of CO<sub>2</sub>-emitting springs, there were *no* significant effects of elevated CO<sub>2</sub> on leaf-litter nitrogen content.

In addition, based on a total of 46 experimental observations, Norby *et al.* determined that elevated atmospheric CO<sub>2</sub> concentrations increased leaf-litter lignin concentrations by an average of 6.5%. However, these increases in lignin content occurred only in woody, but not herbaceous, species. And again, the lignin concentrations of leaf litter were *not* affected by elevated CO<sub>2</sub> when plants were grown in open-top chambers, FACE plots, or in the proximity of CO<sub>2</sub>-emitting springs.

Finally, in an analysis of a total of 101 observations, Norby *et al.* found that elevated CO<sub>2</sub> had no consistent effect on leaf-litter decomposition rate in *any* type of experimental setting. Hence, as the air's CO<sub>2</sub> content continues to rise, it will likely have little to no impact on leaf-litter chemistry and rates of leaf-litter decomposition. Since there will be *more* leaf litter produced in a high-CO<sub>2</sub> world of the future, however, that fact alone will ensure that more carbon is sequestered in the world's soils for longer periods of time.

It must additionally be noted, however, as stated by Agren and Bosatta (2002), that "global warming has long been assumed to lead to an increase in soil respiration and, hence, decreasing soil carbon stores." Indeed, this dictum was accepted as gospel for many years, for a number of laboratory experiments seemed to suggest that nature would not allow more carbon to be sequestered in the soils of a warming world. As one *non*-laboratory experiment after another has recently demonstrated, however, such is *not* the case; and theory has been forced to change to accommodate reality.

The old-school view of things began to unravel in 1999, when two important studies presented evidence refuting the long-standing orthodoxy. Abandoning the laboratory for the world of nature, Fitter *et al.* (1999) heated natural grass ecosystems by 3°C and found that the temperature increase had "no direct effect on the soil carbon store." Even more astounding,

Liski *et al.* (1999) showed that carbon storage in the soils of both high- and low-productivity boreal forests in Finland actually *increased* with rising temperatures along a natural temperature gradient.

The following year saw more of the same. Johnson *et al.* (2000) warmed natural Arctic tundra ecosystems by nearly 6°C for *eight full years* and still found no significant effect of that major temperature increase on ecosystem respiration. Likewise, Giardina and Ryan (2000) analyzed organic carbon decomposition data derived from the forest soils of *82 different sites on five continents*, reporting the amazing fact that "despite a 20°C gradient in mean annual temperature, soil carbon mass loss ... was insensitive to temperature."

What was theory to do? It had to change. What is more, it had to change fast. And it did. The very next year, Thornley and Cannell (2001) ventured forth gingerly with what they called "an hypothesis" concerning the matter. Specifically, they proposed the idea that warming may increase the rate of certain physico-chemical processes that transfer organic carbon from less-stable to more-stable soil organic matter pools, thereby enabling the better-protected organic matter to avoid, or more strongly resist, decomposition. Then, they developed a dynamic soil model in which they demonstrated that if their thinking was correct, long-term soil carbon storage would appear to be insensitive to a rise in temperature, even if the respiration rates of all soil carbon pools rose in response to warming, as they indeed do.

The paper of Agren and Bosatta is an independent parallel development of much the same concept, although they describe the core idea in somewhat different terms, and they upgrade the concept from what Thornley and Cannell call an "hypothesis" to what they refer to as the continuous-quality "theory." *Quality*, in this context, refers to the degradability of soil organic matter; and *continuous quality* suggests there is a wide-ranging continuous spectrum of soil organic carbon "mini-pools" that possess differing degrees of resistance to decomposition.

The continuous quality theory thus states that soils from naturally higher temperature regimes will have soil organic matter "continuous quality" distributions that contain relatively more organic matter in carbon pools that are more resistant to degradation and are consequently characterized by lower rates of decomposition, which has been observed experimentally to be the case by Grisi *et al.* (1998). In addition, it states that this shift in the distribution of soil organic matter qualities, i.e., the higher-temperature-induced creation of more of the more-difficult-to-decompose organic matter, will counteract the decomposition-promoting influence of the higher temperatures, so that the overall decomposition rate of the totality of organic matter in a higher-temperature soil is either unaffected or actually reduced.

Once again, therefore, it would appear that the ongoing rise in the air's CO<sub>2</sub> content, as well as any degree of warming that might possibly accompany it, will not materially alter the rate of decomposition of the world's soil organic matter. Hence, the rate at which carbon is sequestered in the world's soils should continue to increase, as joint function of the rate at which the productivity of earth's plants is increased by the aerial fertilization effect of the rising atmospheric CO<sub>2</sub> concentration and the rate of expansion of the planet's vegetation into drier

regions of the globe that is made possible by the concomitant CO<sub>2</sub>-induced increase in vegetative water use efficiency.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/d/decompprocesses.php>.

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### 7.1.2. Agricultural Crops

Agricultural crops grown at elevated atmospheric CO<sub>2</sub> concentrations nearly always exhibit increased photosynthetic rates and biomass production. Due to this productivity enhancement, more plant material is typically added to soils from root growth, turnover and exudation, as well as from leaves and stems following their abscission during senescence. This plant material often has a greater carbon-to-nitrogen ratio than plant material produced in ambient air. A question thus arises as to whether or not such changes in plant litter quality affect its decomposition rate. Moreover, if any changes do occur, how might they impact biological carbon sequestration? In searching for answers to these important questions, we turn to the scientific literature to see what has recently been published in this field.

In the study of Booker *et al.* (2000), leaves from defoliated cotton plants grown at an atmospheric CO<sub>2</sub> concentration of 720 ppm displayed significantly greater amounts of starch and soluble sugars and significantly lower concentrations of nitrogen than the leaves of plants grown in ambient air. These changes in the quality of the leaf litter produced under high CO<sub>2</sub> likely affected its subsequent decomposition rate, which was 10 to 14% slower than that observed for leaf litter collected from plants grown in air of normal CO<sub>2</sub> concentration. Likewise, when crop residues from soybean and sorghum plants that were raised in twice-ambient CO<sub>2</sub> environments were mixed with soils to study their decomposition rates, Torbert *et al.* (1998) noted that they lost significantly less carbon – up to 40% less – than similarly treated crop residues from ambiently-grown crops.

In contrast to the aforementioned studies, where residues from CO<sub>2</sub>-enriched agricultural crops decomposed at slower rates than residues from crops grown at ambient CO<sub>2</sub> concentrations, neither Van Vuuren *et al.* (2000), for spring wheat, nor Henning *et al.* (1996), for soybean and sorghum, found any significant differences in the decomposition rates of the residues of crops grown under these two conditions of high or normal atmospheric CO<sub>2</sub> concentration.

As the air's CO<sub>2</sub> content continues to rise, therefore, and agricultural crops grow more robustly and return greater amounts of litter to the soil, it is likely that greater amounts of carbon will be sequestered in the soil in which they grew, as crop residue decomposition rates are significantly decreased or remain unchanged.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/d/decompositionagri.php>.

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### 7.1.3. Grassland Species

Grassland species grown at elevated atmospheric CO<sub>2</sub> concentrations nearly always exhibit increased photosynthetic rates and biomass production. Due to this productivity enhancement, more plant material is typically added to soils from root growth, turnover and exudation, as well as from leaves and stems following their abscission during senescence. Such plant material, however, sometimes has a greater carbon-to-nitrogen ratio than plant material produced under ambient CO<sub>2</sub> concentrations. Thus, a question arises as to whether or not such changes in plant litter quality affect its decomposition rate. And if a change in decomposition rate occurs, there is the subsequent question of how that phenomenon might impact biological carbon sequestration. In searching for answers to these thought-provoking questions, we turn to the scientific literature to see what has recently been published in this field.

In the study of Nitschelm *et al.* (1997), white clover exposed to an atmospheric CO<sub>2</sub> concentration of 600 ppm for one growing season channeled 50% more newly-fixed carbon compounds into the soil than similar plants exposed to ambient air. In addition, the clover's roots decomposed at a rate that was 24% slower than that observed for roots of control plants, as has also been reported for white clover by David *et al.* (2001). These observations suggest that soil carbon sequestration under white clover ecosystems will be greatly enhanced as the

air's CO<sub>2</sub> content continues to rise, as was also shown for moderately fertile sandstone grasslands (Hu *et al.*, 2001).

Similar results have been observed with mini-ecosystems comprised entirely of perennial ryegrass. Van Ginkel *et al.* (1996), for example, demonstrated that exposing this species to an atmospheric CO<sub>2</sub> concentration of 700 ppm for two months caused a 92% increase in root growth and 19 and 14% decreases in root decomposition rates one and two-years, respectively, after incubating ground roots within soils. This work was later followed up by Van Ginkel and Gorissen (1998), who showed a 13% reduction in the decomposition rates of CO<sub>2</sub>-enriched perennial ryegrass roots in both disturbed and undisturbed root profiles. This and other work led the authors to calculate that CO<sub>2</sub>-induced reductions in the decomposition of perennial ryegrass litter, which enhances soil carbon sequestration, could well be large enough to remove over half of the anthropogenic CO<sub>2</sub> emissions that may be released in the next century (Van Ginkel *et al.*, 1999). Furthermore, Van Ginkel *et al.* (2000) determined that predicted increases in surface air temperature would not adversely impact the strength of this powerful biological carbon sink. Indeed, after experimentally raising ambient air temperatures by 2 °C, they reported that CO<sub>2</sub>-induced reductions in litter decomposition rates were still 12% slower than those of litter grown in ambient air. In fact, even a 6 °C increase in air temperature could not destroy the CO<sub>2</sub>-induced reductions in litter decomposition rates.

In some cases, atmospheric CO<sub>2</sub> enrichment has little or no significant effects on litter quality and subsequent rates of litter decomposition, as was the case in the study of Hirschel *et al.* (1997) for lowland calcareous and high alpine grassland species. Similar non-effects of elevated CO<sub>2</sub> on litter decomposition have also been reported in a California grassland (Dukes and Field, 2000).

In light of these several experimental findings, it would appear that as the air's CO<sub>2</sub> concentration increases, litter decomposition rates of grassland species will likely decline, increasing the amount of carbon sequestered in grassland soils. Since this phenomenon is augmented by the aerial fertilization effect of atmospheric CO<sub>2</sub> enrichment, which leads to the production of greater amounts of litter, there is thus a double reason for expecting more carbon to be removed from the atmosphere by earth's grasslands in the future.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/d/decompositiongrass.php>.

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#### 7.1.4. Woody Plants

The sequestering of carbon in the soils upon which woody plants grow has the potential to provide a powerful brake on the rate of rise of the air's CO<sub>2</sub> content *if the plant litter that is incorporated into those soils does not decompose more rapidly in a CO<sub>2</sub>-enriched atmosphere than it does in current ambient air*. Hence, it is important to determine if this latter constraint is true or false; and in this section we review this question with respect to litter produced by conifers and deciduous trees.

##### 7.1.4.1. Conifers

Scherzel *et al.* (1998) exposed seedlings of two eastern white pine genotypes to elevated concentrations of atmospheric CO<sub>2</sub> and O<sub>3</sub> in open-top chambers for four full growing seasons, finding no changes in the decomposition rates of the litter of either genotype to the concentration increases of either of these two gases. Likewise, Kainulainen *et al.* (2003) could find no evidence that the litter of 22-year-old Scots pine trees that had been exposed to elevated concentrations of CO<sub>2</sub> and O<sub>3</sub> for three full years decomposed any faster or slower than litter produced in ambient air. In addition, Finzi and Schlesinger (2002) found that the decomposition rate of litter from 13-year-old loblolly pine trees was unaffected by elevated CO<sub>2</sub> concentrations maintained for a period of two full years in a FACE study.

In light of these observations, plus the fact that Saxe *et al.* (1998) have determined that a doubling of the air's CO<sub>2</sub> content leads to *more* than a doubling of the biomass production of coniferous species, it logically follows that the ongoing rise in the atmosphere's CO<sub>2</sub> concentration is increasing carbon sequestration rates in the soils upon which conifers grow and, hence, is producing a significant negative feedback phenomenon that slows the rate of rise of the air's CO<sub>2</sub> content, which would be assumed by many to be reducing the rate of global warming.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/d/decomconifers.php>.

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#### 7.1.4.2. Deciduous Trees

Scherzel *et al.* (1998) exposed seedlings of yellow poplar trees to elevated concentrations of atmospheric CO<sub>2</sub> and O<sub>3</sub> in open-top chambers for four full growing seasons, finding that rates of litter decomposition were similar for all treatments for the first five months of the study. Thereafter, however, litter produced in the elevated O<sub>3</sub> and CO<sub>2</sub> treatment decomposed at a significantly slower rate, such that after two years had passed, the litter from the elevated O<sub>3</sub> and CO<sub>2</sub> treatment contained approximately 12% more biomass than the litter from any other treatment.

Cotrufo *et al.* (1998) grew two-year-old ash and sycamore seedlings for one growing season in closed-top chambers maintained at atmospheric CO<sub>2</sub> concentrations of 350 and 600 ppm. The high-CO<sub>2</sub> air increased lignin contents in the litter produced from both tree species, which likely contributed to the decreased litter decomposition rates observed in the CO<sub>2</sub>-enriched chambers. After one-year of incubation, for example, litter bags from the CO<sub>2</sub>-enriched trees of both species had about 30% more dry mass remaining in them than litter bags from the ambient trees. In addition, woodlouse arthropods consumed 16% *less* biomass when fed litter



generated from seedlings grown at 600 ppm CO<sub>2</sub> than when fed litter generated from seedlings grown in ambient air.

De Angelis *et al.* (2000) constructed large open-top chambers around 30-year-old mixed stands of naturally growing Mediterranean forest species (dominated by *Quercus ilex*, *Phillyrea angustifolia*, and *Pistacia lentiscus*) near the coast of central Italy. Half of the chambers were exposed to ambient air of 350 ppm CO<sub>2</sub>, while half were exposed to air of 710 ppm CO<sub>2</sub>; and after three years, the lignin and carbon concentrations of the leaf litter of all three species were increased by 18 and 4%, respectively, while their nitrogen concentrations were reduced by 13%. These changes resulted in a 20% CO<sub>2</sub>-induced increase in the carbon-to-nitrogen ratio of the leaf litter, which parameter is commonly used to predict decomposition rates, where larger ratios are generally associated with less rapid decomposition than smaller ratios. This case was no exception, with 4% less decomposition occurring in the leaf litter gathered from beneath the CO<sub>2</sub>-enriched trees than in the litter collected from beneath the trees growing in ambient air.

Cotrufo and Ineson (2000) grew beech seedlings for five years in open-top chambers fumigated with air containing either 350 or 700 ppm CO<sub>2</sub>. Subsequently, woody twigs from each CO<sub>2</sub> treatment were collected and incubated in native forest soils for 42 months, after which they determined there was no significant effect of the differential CO<sub>2</sub> exposure during growth on subsequent woody twig decomposition, although the mean decomposition rate of the CO<sub>2</sub>-enriched twigs was 5% less than that of the ambient-treatment twigs.

Conway *et al.* (2000) grew two-year-old ash tree seedlings in solardomes maintained at atmospheric CO<sub>2</sub> concentrations of 350 and 600 ppm, after which naturally-senesced leaves were collected, inoculated with various fungal species, and incubated for 42 days. They found that the elevated CO<sub>2</sub> significantly reduced the amount of nitrogen in the senesced leaves, thus giving the CO<sub>2</sub>-enriched leaf litter a higher carbon to nitrogen ratio than the litter collected from the seedlings growing in ambient air. This change likely contributed to the observed reductions in the amount of fungal colonization present on the senesced leaves from the CO<sub>2</sub>-enriched treatment, which would be expected to result in reduced rates of leaf decomposition.

King *et al.* (2001) grew aspen seedlings for five months in open-top chambers receiving atmospheric CO<sub>2</sub> concentrations of 350 and 700 ppm. At the end of this period, naturally senesced leaf litter was collected, analyzed and allowed to decompose under ambient conditions for 111 days. Although the elevated CO<sub>2</sub> slightly lowered leaf litter nitrogen content, it had no effect on litter sugar, starch or tannin concentrations. Thus, with little to no CO<sub>2</sub>-induced effects on leaf litter quality, it was not surprising there was no CO<sub>2</sub>-induced effect on litter decomposition.

Dilustro *et al.* (2001) erected open-top chambers around portions of a regenerating oak-palmetto scrub ecosystem in Florida, USA, and maintained them at CO<sub>2</sub> concentrations of either 350 or 700 ppm, after which they incubated ambient- and elevated-CO<sub>2</sub>-produced fine roots for 2.2 years in the chamber soils, which were nutrient-poor and often water-stressed. They found that the elevated CO<sub>2</sub> did not significantly affect the decomposition rates of the fine roots originating from either the ambient or CO<sub>2</sub>-enriched environments.

In summarizing the results of these seven studies of deciduous tree species, five are suggestive of slight *reductions* in litter decomposition rates under CO<sub>2</sub>-enriched growth conditions, while two show no effect. Hence, with deciduous trees exhibiting large growth enhancements in response to atmospheric CO<sub>2</sub> enrichment, we can expect to see large increases in the amounts of carbon they sequester in the soils on which they grow as the air's CO<sub>2</sub> content continues to rise. And this phenomenon should slow the rate of rise of the atmosphere's CO<sub>2</sub> concentration and thereby reduce the impetus for CO<sub>2</sub>-induced global warming.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/d/decompdeciduous.php>.

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## 7.2. Agriculture

### 7.2.1. General

Agricultural and forage plants grown in elevated CO<sub>2</sub> concentrations nearly always exhibit increased photosynthetic rates and biomass production. Because of this greater growth, more

plant material is typically added to soils from root growth, turnover, and exudation, as well as from leaves and stems following their abscission during senescence. Consequently, these phenomena tend to increase soil carbon contents in CO<sub>2</sub>-enriched atmospheres.

In an open-top chamber experiment conducted in Switzerland, for example, Nitschelm *et al.* (1997) reported that a 71% increase in the atmospheric CO<sub>2</sub> concentration above white clover monocultures led to a 50% increase in soil organic carbon content. Related studies on wheat and soybean agroecosystems (Islam *et al.*, 1999) provided similar results, as did a FACE experiment on cotton, which documented a 10% increase in soil organic carbon content in plots receiving 550 ppm CO<sub>2</sub> relative to those receiving 370 ppm (Leavitt *et al.*, 1994).

Atmospheric CO<sub>2</sub> enrichment not only increases the amount of carbon entering soils, but it often maintains (Henning *et al.*, 1996), or even increases, its residency time within that significant carbon pool. Torbert *et al.* (1998), for example, demonstrated that decomposition rates of CO<sub>2</sub>-enriched sorghum and soybean plant litter were significantly less than those measured for control litter produced at ambient CO<sub>2</sub> concentration, as did Nitschelm *et al.* (1997), who reported a 24% decrease in the decomposition of CO<sub>2</sub>-enriched white clover roots. Furthermore, after two months of decomposition in the experiment of Torbert *et al.* (1998), 40% less carbon had evolved from soils containing CO<sub>2</sub>-enriched plant litter.

In summary, these studies demonstrate that atmospheric CO<sub>2</sub> enrichment will likely increase soil carbon inputs while either maintaining or decreasing CO<sub>2</sub> efflux from agricultural soils. Thus, as the CO<sub>2</sub> content of the air increases, these two interacting phenomena will likely increase the carbon sequestering abilities of earth's agroecosystems. Moreover, as the organic carbon contents of agricultural soils increase, soil structure and quality will simultaneously be improved, which should enhance plant growth even more, leading to additional carbon sequestration under CO<sub>2</sub>-enriched conditions (Rasmussen *et al.*, 1998; Islam *et al.*, 1999).

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/c/carbonag.php>.

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### 7.2.2. CO<sub>2</sub> x Temperature Interaction

Rising CO<sub>2</sub> levels tend to maintain (Henning *et al.*, 1996) or decrease (Torbert *et al.*, 1998; Nitschelm *et al.*, 1997) CO<sub>2</sub> fluxes from agricultural soils. Consequently, these phenomena tend to increase the carbon contents of most soils in CO<sub>2</sub>-enriched atmospheres. However, it is sometimes suggested that rising air temperatures, which can accelerate the breakdown of soil organic matter and increase biological respiration rates, could negate this CO<sub>2</sub>-induced enhancement of carbon sequestration, possibly leading to an even greater release of carbon back to the atmosphere. Thus, we turn to the scientific literature for added light on this issue.

Casella and Soussana (1997) grew perennial ryegrass in controlled environments receiving ambient and elevated (700 ppm) atmospheric CO<sub>2</sub> concentrations, two levels of soil nitrogen, and ambient and elevated (+3°C) air temperatures for a period of two years, finding that "a relatively large part of the additional photosynthetic carbon is stored below-ground during the two first growing seasons after exposure to elevated CO<sub>2</sub>, thereby increasing significantly the below-ground carbon pool." At the low and high levels of soil nitrogen supply, for example, the elevated CO<sub>2</sub> increased soil carbon storage by 32 and 96%, respectively, "with no significant increased temperature effect." The authors thus concluded that *in spite of predicted increases in temperature*, "this stimulation of the below-ground carbon sequestration in temperate grassland soils could exert a negative feed-back on the current rise of the atmospheric CO<sub>2</sub> concentration."

Much the same conclusion was reached by Van Ginkel *et al.* (1999). After reviewing prior experimental work that established the growth and decomposition responses of perennial ryegrass to both atmospheric CO<sub>2</sub> enrichment and increased temperature, these researchers concluded that, at both low and high soil nitrogen contents, CO<sub>2</sub>-induced increases in plant growth and CO<sub>2</sub>-induced *decreases* in plant decomposition rate are more than sufficient to counteract any enhanced soil respiration rate that might be caused by an increase in air temperature. In addition, after reconstructing carbon storage in the terrestrial vegetation of Northern Eurasia as far back as 125,000 years ago, Velichko *et al.* (1999) determined that plants in this part of the world were more productive and efficient in sequestering carbon at higher temperatures than they were at lower temperatures. Similarly, Allen *et al.*, (1999) used sediment cores from a lake in southern Italy and from the Mediterranean Sea to conclude that,

over the past 102,000 years, warmer climates have been better for vegetative productivity and carbon sequestration than have cooler climates.

In our own day, Liski *et al.* (1999) studied soil carbon storage across a temperature gradient in a Finnish boreal forest, determining that carbon sequestration in the soil of this forest *increased* with temperature. In deciduous forests of the eastern United States, White *et al.* (1999) also determined that persistent increases in growing season length (due to rising air temperatures) may lead to long-term increases in carbon storage, which, of course, tends to counterbalance - indeed, *overpower* - the effects of increasing air temperature on respiration rates. In fact, a data-driven analysis by Fan *et al.* (1998) suggests that the carbon sequestering abilities of North America's forests between 15 and 51°N latitude are so robust that they can yearly remove from the atmosphere all of the CO<sub>2</sub> annually released to it by fossil fuel consumption in both the United States and Canada (and this calculation was done during a time touted as having the warmest temperatures on record). Moreover, Phillips *et al.* (1998) have shown that carbon sequestration in tropical forests has increased substantially over the past 42 years, in spite of any temperature increases that may have occurred during that time.

In conclusion, research conducted to date strongly suggests that the CO<sub>2</sub>-induced enhancement of vegetative carbon sequestration will not be reduced by any future rise in air temperature, regardless of its cause. In fact, it is likely that in a CO<sub>2</sub>-enriched atmosphere, any increase in temperature will actually *enhance* biological carbon sequestration.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/c/carbonco2temp.php>.

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## **7.3. Forests**

### **7.3.1. General**

As the CO<sub>2</sub> content of the air continues to rise, nearly all of earth's plants, including various forest ecosystems, will respond by increasing their photosynthetic rates and producing more biomass. These phenomena will allow long-lived perennial species characteristic of forest ecosystems to sequester large amounts of carbon within their wood for extended periods of time (Chambers *et al.*, 1998), which could ultimately counterbalance CO<sub>2</sub> emissions produced by mankind's usage of fossil fuels. Thus, it is important to summarize what is known about forest and forest-species responses to atmospheric CO<sub>2</sub> enrichment and subsequent carbon sequestration.

In reviewing studies that have been conducted on individual trees, it is clear that elevated levels of atmospheric CO<sub>2</sub> increase photosynthesis and growth in both broad-leaved and coniferous species. When broad-leaved trembling aspen (*Populus tremuloides*) were exposed to twice-ambient levels of atmospheric CO<sub>2</sub> for 2.5 years, for example, Pregitzer *et al.* (2000) reported 17

and 65% increases in fine root biomass at low and high levels of soil nitrogen, respectively; while Zak *et al.* (2000) observed 16 and 38% CO<sub>2</sub>-induced increases in total tree biomass when subjected to the same respective levels of soil nitrogen.

Similar results have been reported for coniferous trees. When branches of Sitka spruce (*Picea sitchensis*) were fumigated with air of 700 ppm CO<sub>2</sub> for four years, rates of net photosynthesis in current and second-year needles were 100 and 43% higher, respectively, than photosynthetic rates of needles exposed to ambient air (Barton and Jarvis, 1999). In addition, ponderosa pine (*Pinus ponderosa*) grown at 700 ppm CO<sub>2</sub> for close to 2.5 years exhibited rates of net photosynthesis in current-year needles that were 49% greater than those of needles exposed to air containing 350 ppm CO<sub>2</sub> (Houpis *et al.*, 1999). Many more such responses of trees to atmospheric CO<sub>2</sub> enrichment can also be found in our Subject Index under the general heading of Trees.

From the preceding material, it is clear that elevated CO<sub>2</sub> enhances photosynthetic rates and biomass production in forest trees, both of which phenomena lead to greater amounts of carbon sequestration. In addition, elevated CO<sub>2</sub> enhances carbon sequestration by reducing carbon losses arising from plant respiration. Karnosky *et al.* (1999), for example, reported that aspen seedlings grown for one year at 560 ppm CO<sub>2</sub> displayed dark respiration rates that were 24% lower than rates exhibited by trembling aspen grown at 360 ppm CO<sub>2</sub>. Also, elevated CO<sub>2</sub> has been shown to decrease maintenance respiration, which it did by 60% in western hemlock seedlings exposed to an atmospheric CO<sub>2</sub> concentration of nearly 1600 ppm (McDowell *et al.*, 1999).

In a thorough review of these topics, Drake *et al.* (1999) concluded that, on average, a doubling of the atmospheric CO<sub>2</sub> concentration reduces plant respiration rates by approximately 17%. This finding contrasts strikingly with the much smaller effects reported by Amthor (2000), who found an average reduction in dark respiration of only 1.5% for nine deciduous trees species exposed to 800 ppm CO<sub>2</sub>. The period of CO<sub>2</sub> exposure in his much shorter experiments, however, was but a mere 15 minutes. Hence, if the air's CO<sub>2</sub> content doubles, plants will likely sequester something on the order of 17% more carbon than ambiently-grown plants, solely as a consequence of CO<sub>2</sub>-induced reductions in respiration. And it is good to remember that this stored carbon is in addition to that sequestered as a result of CO<sub>2</sub>-induced increases in plant photosynthetic rates.

What is the fate of the extra carbon that is stored within plant tissues as a consequence of atmospheric CO<sub>2</sub> enrichment? Is it rapidly returned to the atmosphere following tissue senescence and decomposition? Or is it somehow locked away for long periods of time?

To answer these questions, it is important to note that atmospheric CO<sub>2</sub> enrichment typically reduces, or has no effect upon, decomposition rates of senesced plant material. De Angelis *et al.* (2000), for example, noted that when leaf litter from Mediterranean forest species exposed to 710 ppm CO<sub>2</sub> for 3.5 years was collected and allowed to decompose at 710 ppm CO<sub>2</sub> for approximately one year, it decomposed at a rate that was 4% less than that observed for leaf

litter produced and incubated at ambient CO<sub>2</sub> concentrations for one year. Similarly, leaf litter collected from yellow-poplar (*Liriodendron tulipifera*) seedlings exposed to 700 ppm CO<sub>2</sub> for four years contained 12% more biomass than leaf litter collected from seedlings grown at ambient CO<sub>2</sub>, following two years of decomposition at their respective CO<sub>2</sub> growth concentrations (Scherzel *et al.*, 1998). However, Hirschel *et al.* (1997) found no significant CO<sub>2</sub>-induced effects on decomposition rates in tropical rainforest species, as Scherzel *et al.* (1998) also found for eastern white pine (*Pinus strobes*). Thus, it would appear that elevated CO<sub>2</sub> typically reduces or has no effect upon plant litter decomposition rates. In addition, it is important to note that none of these decomposition studies looked at *wood*, which can sequester carbon for long periods of time, *even for millennia* (Chambers *et al.*, 1998), provided it is not burned.

Based upon several different types of empirical data, a number of researchers have concluded that current rates of carbon sequestration are robust and that future rates will increase with increasing atmospheric CO<sub>2</sub> concentrations. In the study of Fan *et al.* (1998) based on atmospheric measurements, for example, the broad-leaved forested region of North America between 15 and 51°N latitude was calculated to possess a current carbon sink that can annually remove all the CO<sub>2</sub> emitted into the air from fossil fuel combustion in both Canada and the United States. On another large scale, Phillips *et al.* (1998) used data derived from tree basal area to show that average forest biomass in the tropics has increased substantially over the last 40 years and that growth in the Neotropics alone can account for 40% of the missing carbon of the entire globe. And in looking to the future, White *et al.* (2000) have calculated that coniferous and mixed forests north of 50°N latitude will likely expand their northern and southern boundaries by about 50% due to the combined effects of increasing atmospheric CO<sub>2</sub>, rising temperature, and nitrogen deposition.

The latter of these factors is an important variable. As indicated in the study of White *et al.* (2000), it can play an interactive role with increasing atmospheric CO<sub>2</sub> to increase plant growth and carbon sequestration. However, the magnitude of that role is still being debated. Nadelhoffer *et al.* (1999), for example, concluded that nitrogen deposition from human activities is "unlikely to be a major contributor" to the large CO<sub>2</sub> sink that exists in northern temperate forests. Houghton *et al.* (1998), however, feel that nitrogen deposition holds equal weight with CO<sub>2</sub> fertilization in the production of terrestrial carbon sinks; and Lloyd (1999) demonstrated that when CO<sub>2</sub> and nitrogen increase together, modeled forest productivity is greater than that predicted by the sum of the individual contributions of these two variables. Thus, anthropogenic nitrogen deposition can have anywhere from small to large positive effects on carbon sequestration, as well as everything in between.

In spite of these many positive findings, some have expressed concern that rising air temperatures will negatively impact carbon sequestration in forests. However, Liski *et al.* (1999) showed that carbon storage in soils of both high- and low-productivity boreal forests in Finland actually *increased* with increasing temperature, thereby putting to rest the idea that rising temperatures will spur carbon losses from soils and trees and exacerbate global warming. Similarly, King *et al.* (1999) showed that aspen seedlings increased their



photosynthetic rates and biomass production as temperatures rose from 10 to 29°C, putting to rest the idea that high-temperature-induced increases in respiration rates would cause net losses in carbon fixation. Moreover, White *et al.* (1999) showed that rising temperatures increased the growing season by about 15 days for 12 sites in deciduous forests located within the United States, causing a 1.6% increase in net ecosystem productivity per day. Thus, rather than exerting a negative influence on forest carbon sequestration, if air temperatures rise in the future they will likely have a positive effect on carbon storage in forests and their associated soils.

In conclusion, as the air's CO<sub>2</sub> content continues to rise, the ability of earth's forests to sequester carbon should also rise. With more CO<sub>2</sub> in the atmosphere, trees will likely exhibit greater rates of photosynthesis and reduced rates of respiration. Together, these observations - along with the finding that atmospheric CO<sub>2</sub> enrichment has little or no effect on plant tissue decomposition rate - suggest that biologically-fixed carbon will experience greater residency times within plant tissues. And if this carbon is directed into wood production, which increases substantially with atmospheric CO<sub>2</sub> enrichment, some of it can be kept out of circulation for a very long time, possibly even a millennium or more.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/c/carbonforests.php>.

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### 7.3.2. Old Forests

According to the Technical Support Document of the ASPR, "rising CO<sub>2</sub> will very likely increase photosynthesis for forests, but this increase will likely only enhance wood production in young forests on fertile soils." In this section, we highlight the results of several peer-reviewed scientific journal articles that suggest this statement is not correct. In addition to enhancing the growth and production of young forests, available research clearly indicates that rising atmospheric CO<sub>2</sub> concentrations have been and will continue to increase the productivity and growth of older forests.

For most of the past century it was believed that old-growth forests, such as those of Amazonia, should be close to dynamic equilibrium. Just the opposite, however, has been repeatedly observed over the past two decades.

In one of the first studies to illuminate this reality, Phillips and Gentry (1994) analyzed the turnover rates - which are close correlates of net productivity (Weaver and Murphy, 1990) - of forty tropical forests from all around the world. They found that the growth rates of these already highly productive forests had been rising ever higher since at least 1960, and that they had experienced an apparent acceleration in growth rate sometime after 1980. Commenting on these findings, Pimm and Sugden (1994) reported that the consistency and simultaneity of the forest growth trends that Phillips and Gentry had documented on several continents led them to conclude that "enhanced productivity induced by increased CO<sub>2</sub> is the most plausible candidate for the cause of the increased turnover."

A few years later, Phillips *et al.* (1998) analyzed forest growth rate data for the period 1958 to 1996 for several hundred plots of mature tropical trees scattered around the world, finding that tropical forest biomass, as a whole, increased substantially over the period of record. In fact, the increase in the Neotropics was equivalent to approximately 40% of the missing terrestrial

carbon sink of the entire globe. Consequently, they concluded that tropical forests "may be helping to buffer the rate of increase in atmospheric CO<sub>2</sub>, thereby reducing the impacts of global climate change." And, again, they identified the aerial fertilization effect of the ongoing rise in the air's CO<sub>2</sub> content as one of the primary factors likely to be responsible for this phenomenon.

More recently, Laurance *et al.* (2004a) reported accelerated growth in the 1990s relative to the 1980s for the large majority (87%) of tree genera in 18 one-hectare plots spanning an area of about 300 km<sup>2</sup> in central Amazonia, while Laurance *et al.* (2004b) observed similarly accelerated tree community dynamics in the 1990s relative to the 1980s. In addition, Baker *et al.* (2004) reported there has been a net increase in biomass in old-growth Amazonian forests in recent decades at a rate of  $1.22 \pm 0.42 \text{ Mg ha}^{-1} \text{ yr}^{-1}$ , slightly greater than that originally estimated by Phillips *et al.* (1998). And once again, it was suggested, in the words of Laurance *et al.* (2005), that these "pervasive changes in central Amazonian tree communities were most likely caused by global- or regional-scale drivers, such as increasing atmospheric CO<sub>2</sub> concentrations (Laurance *et al.*, 2004a,b)."

Expanding upon this theme, Laurance *et al.* (2005) say they "interpreted these changes as being consistent with an ecological 'signature' expected from increasing forest productivity (cf., Phillips and Gentry, 1994; Lewis *et al.* 2004a,b; Phillips *et al.*, 2004)." They note, however, that they have been challenged in this conclusion by Nelson (2005), and they thus go on to consider his arguments in some detail, methodically dismantling them one by one.

Evidence of increasing dynamism and productivity of intact tropical forests continued, with Lewis *et al.*, (2004a) reporting that among 50 old-growth plots scattered across tropical South America, "stem recruitment, stem mortality, and biomass growth, and loss, *all* increased significantly." In summarizing these and other findings, Lewis (2006) reports that over the past two decades, "these forests have shown concerted changes in their ecology, becoming, on average, faster growing - more productive - and more dynamic, and showing a net increase in above-ground biomass," all of which rates of increase are greater than the previously documented increases in the rates of these phenomena. What is more, Lewis says that "preliminary analyses also suggest the African and Australian forests are showing structural changes similar to South American forests."

So why should we care about growth trends of old forests?

The planting and preservation of forests has long been acknowledged to be an effective and environmentally-friendly (indeed, *enhancing*) means for slowing climate-model-predicted CO<sub>2</sub>-induced global warming. This prescription for moderating potential climate change is based on two well-established and very straightforward facts: (1) the carbon trees use to construct their tissues comes from the air, and (2) its extraction from the atmosphere slows the rate of rise of the air's CO<sub>2</sub> content.

Although simple enough that a child can understand it, this potential partial solution to the putative global warming problem has been under attack for several years by people who seek to address the issue solely on the basis of forced reductions in anthropogenic CO<sub>2</sub> emissions (Pearce, 1999). The tack they take in this campaign is to claim that carbon sequestration by forests is only viable when forests are young and growing vigorously. As forests age, as claimed in the CRDs, they gradually lose their carbon sequestering prowess, such that forests more than one hundred years old become essentially useless for removing CO<sub>2</sub> from the air, as they claim such ancient and decrepit stands yearly lose as much CO<sub>2</sub> via respiration as what they take in via photosynthesis.

Although demonstrably erroneous, with repeated telling the twisted tale actually begins to sound reasonable. After all, doesn't the metabolism of every living thing slow down as it gets older? We grudgingly admit that it does -- even with trees -- but some trees live a remarkably long time. In Panama (Condit *et al.*, 1995), Brazil (Chambers *et al.*, 1998; Laurance *et al.*, 2004; Chambers *et al.*, 2001), and many parts of the southwestern United States (Graybill and Idso, 1993), for example, individuals of a number of different species have been shown to live for nearly one and a half *millennia*. At a hundred years of age, these super-slurpers of CO<sub>2</sub> are mere *youngsters*. And in their *really* old age, their appetite for the vital gas, though diminished, is not lost. In fact, Chambers *et al.* (1998) indicate that the long-lived trees of Brazil continue to experience protracted slow growth *even at 1400 years of age*. And protracted slow growth (evident in yearly increasing trunk diameters) of very old and *large* trees can absorb a huge amount of CO<sub>2</sub> out of the air each year, especially when, as noted by Chambers *et al.* (1998) with respect to the Brazilian forests in the central Amazon, about 50% of their above-ground biomass is contained in less than the largest 10% of their trees. Consequently, since the life span of these massive long-lived trees is considerably greater than the projected life span of the entire "Age of Fossil Fuels," their cultivation and preservation represents an essentially *permanent* partial solution to the perceived problem of the dreaded global warming that climate alarmists ascribe to anthropogenic CO<sub>2</sub> emissions.

As important as are these facts about *trees*, however, there's an even more important fact that comes into play in the case of *forests* and their ability to sequester carbon over long periods of time. This little-acknowledged piece of information is the fact that it is the forest itself -- conceptualized as a huge super-organism, if you will -- that is the unit of primary importance when it comes to determining the ultimate amount of carbon that can be sequestered on a unit area of land. And it when it comes to elucidating this concept, it seems that a lot of climate alarmists and political opportunists can't seem to see the forest for the trees that comprise it.

That this difference in perspective can have enormous consequences has been clearly demonstrated by Cary *et al.* (2001), who note that most models of forest carbon sequestration *wrongly* assume that "age-related growth trends of individual trees and even-aged, monospecific stands can be extended to natural forests." When they compared the predictions of such models against real-world data they gathered from northern Rocky Mountain subalpine forests that ranged in age from 67 to 458 years, for example, they found that aboveground net primary productivity in 200-year-old natural stands was almost *twice* as great as that of

modeled stands, and that the difference between the two increased linearly throughout the entire sampled age range.

So what's the explanation for the huge discrepancy? Cary *et al.* suggest that long-term *recruitment* and the periodic appearance of additional late-successional species (increasing biodiversity) may have significant effects on stand productivity, infusing the primary unit of concern, i.e., the ever-evolving forest super-organism, with greater vitality than would have been projected on the basis of characteristics possessed by the unit earlier in its life. They also note that by not including effects of size- or age-dependent decreases in stem and branch respiration per unit of sapwood volume in models of forest growth, respiration in older stands can be over-estimated by a factor of two to five.

How serious are these model shortcomings? For the real-world forests studied by Cary *et al.*, they produce predictions of carbon sequestration that are only a little over half as large as what is observed in nature for 200-year-old forests; while for 400-year-old forests they produce results that are only about a third as large as what is characteristic of the real world. And as the forests grow older still, the difference between reality and model projections grows right along with them.

Another study relevant to the suitability of forests to act as long-term carbon sinks was conducted by Lou *et al.* (2003), who analyzed data obtained from the Duke Forest FACE experiment, in which three 30-meter-diameter plots within a 13-year old forest (composed primarily of loblolly pines with sweetgum and yellow poplar trees as sub-dominants, together with numerous other trees, shrubs and vines that occupy still smaller niches) began to be enriched with an extra 200 ppm of CO<sub>2</sub> in August of 1996, while three similar plots were maintained at the ambient atmospheric CO<sub>2</sub> concentration. A number of papers describing different facets of this still-ongoing long-term study have been published; and as recounted by Lou *et al.*, they have revealed the existence of a CO<sub>2</sub>-induced "sustained photosynthetic stimulation at leaf and canopy levels [Myers *et al.*, 1999; Ellsworth, 2000; Luo *et al.*, 2001; Lai *et al.*, 2002], which resulted in sustained stimulation of wood biomass increment [Hamilton *et al.*, 2002] and a larger carbon accumulation in the forest floor at elevated CO<sub>2</sub> than at ambient CO<sub>2</sub> [Schlesinger and Lichten, 2001]."

Based upon these findings and what they imply about rates of carbon removal from the atmosphere and its different residence times in plant, litter and soil carbon pools, Luo *et al.* developed a model for studying the sustainability of forest carbon sequestration. Applying this model to a situation where the atmospheric CO<sub>2</sub> concentration gradually rises from a value of 378 ppm in 2000 to a value of 710 ppm in 2100, they calculated that the carbon sequestration rate of the Duke Forest would rise from an initial value of 69 g m<sup>-2</sup> yr<sup>-1</sup> to a final value of 201 g m<sup>-2</sup> yr<sup>-1</sup>, which is a far, far cry from the sad scenario promulgated by the cadre of climate alarmists that have long claimed earth's forests will have released much of the carbon they had previously absorbed as early as the year 2050 (Pearce, 1999).

Another study that supports the long-term viability of carbon sequestration by forests was conducted by Paw U *et al.* (2004), who also note that old-growth forests have generally been considered to "represent carbon sources or are neutral (Odum, 1963, 1965)," stating that "it is generally assumed that forests reach maximum productivity at an intermediate age and productivity declines in mature and old-growth stands (Franklin, 1988), presumably as dead woody debris and other respiratory demands increase." More particularly, they report that a number of articles have suggested that "old-growth conifer forests are at equilibrium with respect to net ecosystem productivity or net ecosystem exchange (DeBell and Franklin, 1987; Franklin and DeBell, 1988; Schulze *et al.*, 1999), as an age-class end point of ecosystem development."

To see if these claims had any merit, Paw U *et al.* used an eddy covariance technique to estimate the CO<sub>2</sub> exchange rate of the oldest forest ecosystem (500 years old) in the AmeriFlux network of carbon-flux measurement stations -- the Wind River old-growth forest in southwestern Washington, USA, which is composed mainly of Douglas-fir and western Hemlock -- over a period of 16 months, from May 1998 to August 1999. Throughout this period, the fourteen scientists report "there were no monthly averages with net release of CO<sub>2</sub>," and that the cumulative net ecosystem exchange showed "remarkable sequestration of carbon, comparable to many younger forests." Hence, they concluded that "in contrast to frequently stated opinions, old-growth forests can be significant carbon sinks," noting that "the old-growth forests of the Pacific Northwest can contribute to optimizing carbon sequestration strategies while continuing to provide ecosystem services essential to supporting biodiversity."

Yet another study to ask and address the question "Do old forests gain or lose carbon?" was that of Binkley *et al.* (2004), who revisited an aging aspen forest in the Tesuque watershed of northern New Mexico, USA -- which between 1971 and 1976 (when it was between 90 and 96 years old) was thought to have had a *negative* net ecosystem production rate of  $-2.0 \text{ Mg ha}^{-1} \text{ yr}^{-1}$  -- and measured the basal diameters of all trees in the central 0.01 ha of each of 27 plots arrayed across the watershed, after which they used the same regression equations employed in the earlier study to calculate live tree biomass as of 2003.

"Contrary to expectation," as they describe it, Binkley *et al.* report that "live tree mass in 2003 [ $186 \text{ Mg ha}^{-1}$ ] was significantly greater than in 1976 [ $149 \text{ Mg ha}^{-1}$ ] ( $P = 0.02$ ), refuting the hypothesis that live tree mass declined." In fact, they found that the annual net increment of live tree mass was about  $1.37 \text{ Mg ha}^{-1} \text{ yr}^{-1}$  from age 96 to age 123 years, which is only 12% less than the mean annual increment of live tree mass experienced over the forest's initial 96 years of existence ( $149 \text{ Mg ha}^{-1} / 96 \text{ yr} = 1.55 \text{ Mg ha}^{-1} \text{ yr}^{-1}$ ). Consequently, in response to the question they posed when embarking on their study -- "Do old forests gain or lose carbon?" -- Binkley *et al.* concluded that "old aspen forests continue to accrue live stem mass well into their second century, despite declining current annual increments," which, we might add, are not all that much smaller than those the forests exhibited in their younger years.

Similar results have been obtained by Hollinger *et al.* (1994) for a 300-year-old *Nothofagus* site in New Zealand, by Law *et al.* (2001) for a 250-year-old ponderosa pine site in the northwestern

United States, by Falk *et al.* (2002) for a 450-year-old Douglas fir/western hemlock site in the same general area, and by Knohl *et al.* (2003) for a 250-year-old deciduous forest in Germany. In commenting on these findings, the latter investigators say they found "unexpectedly high carbon uptake rates during 2 years for an unmanaged 'advanced' beech forest, which is in contrast to the widely spread hypothesis that 'advanced' forests are insignificant as carbon sinks." For the forest they studied, as they describe it, "assimilation is clearly not balanced by respiration, although this site shows typical characteristics of an 'advanced' forest at a comparatively late stage of development."

These observations about forests are remarkably similar to recent findings regarding humans, i.e., that nongenetic interventions, even late in life, can put one on a healthier trajectory that extends productive lifespan. So what is the *global* "intervention" that has put the planet's trees on the healthier trajectory of being able to sequester significant amounts of carbon in their old age, when *past theory* (which was obviously based on *past observations*) decreed they should be in a state of no-net-growth or even *negative* growth?

The answer, to us, seems rather simple. For any tree of age 250 years or more, the greater portion of its life (at least two-thirds of it) has been spent in an atmosphere of much-reduced CO<sub>2</sub> content. Up until 1920, for example, the air's CO<sub>2</sub> concentration had never been above 300 ppm throughout the entire lives of such trees, whereas it is currently 375 ppm or 25% higher. And for older trees, even *greater* portions of their lives have been spent in air of even *lower* CO<sub>2</sub> concentration. Hence, the "intervention" that has given *new life to old trees* and allows them to "live long and prosper," would appear to be the *aerial fertilization effect* produced by the flooding of the air with CO<sub>2</sub> that resulted from the Industrial Revolution and is being maintained by its ever-expanding aftermath (Idso, 1995).

Based on these many observations, as well as the results of the study of Greenep *et al.* (2003), which strongly suggest, in their words, that "the capacity for enhanced photosynthesis in trees growing in elevated CO<sub>2</sub> is unlikely to be lost in subsequent generations," it would appear that earth's forests will remain strong sinks for atmospheric carbon far beyond the date at which the world's climate alarmists have long proclaimed they would have given back to the atmosphere most of the carbon they had removed from it over their existence to that point in time.

At the end of the day, it thus appears that a large body of scientists agrees that a wealth of scientific data confirms the reality of the ever-increasing productivity of earth's older forests, especially those of Amazonia; and they tend to agree that the concomitant rise in the air's CO<sub>2</sub> content has had much to do with this phenomenon. We also agree, noting that an even greater wealth of laboratory and field data demonstrates that rising forest productivity is exactly what one would expect to observe in response to the stimulus provided by the ongoing rise in the atmosphere's CO<sub>2</sub> concentration.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/f/forestold.php>.



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#### **7.4. Peatlands**

Putative CO<sub>2</sub>-induced global warming has long been predicted to turn boreal and tundra biomes into carbon sources extraordinaire. In fact, until just a few short years ago it was nearly universally believed that rising air temperatures would lead to the thawing of extensive areas of permafrost and the subsequent decomposition of their vast stores of organic matter, which, it was thought, would release much of the peatlands' tightly-held carbon, enabling it to make its way back to the atmosphere as CO<sub>2</sub>. Improved soil drainage and increased aridity were also envisioned to help the process along, possibly freeing enough carbon at a sufficiently rapid rate to rival the amount released to the atmosphere as CO<sub>2</sub> by all anthropogenic sources combined. The end result was claimed to be a tremendous *positive feedback* to the ongoing rise in the air's CO<sub>2</sub> content, which was envisioned to produce a greatly amplified atmospheric greenhouse effect that would lead to catastrophic global warming. In a slight variation of an old maxim, however, this scenario was simply *too bad to be true*. Why? Because it did not even *begin* to deal with the incredible complexity of the issue, several important neglected aspects of which have been briefly described by Weintraub and Schimel (2005).

One of the first cracks in the seemingly sound hypothesis was revealed by the study of Oechel *et al.* (2000), wherein long-term measurements of net ecosystem CO<sub>2</sub> exchange rates in wet-sedge and moist-tussock tundra communities of the Alaskan Arctic indicated that these ecosystems were gradually changing from carbon sources to carbon sinks. The ultimate transition occurred between 1992 and 1996, at the apex of a regional warming trend that culminated with the highest summer temperature and surface water deficit of the previous four decades.

How did it happen, this dramatic and unexpected biological transformation? The answer of the scientists who documented the phenomenon was that it was really nothing special: no more, as they put it, than "a previously undemonstrated capacity for ecosystems to metabolically adjust to long-term changes in climate." Yes, just as people can change their behavior in response to environmental stimuli, so can plants. And this simple ecological acclimation process is only one of several newly-recognized phenomena that have caused scientists to radically revise the way they think about global change in Arctic regions.

Another important study in this area was conducted by Camill *et al.* (2001), who investigated (1) changes in peat accumulation across a regional gradient of mean annual temperature in Manitoba, Canada, (2) net aboveground primary production and decomposition for major functional plant groups of the region, and (3) soil cores from several frozen and thawed bog sites that were used to determine long-term changes in organic matter accumulation following the thawing of boreal peatlands. In direct contradiction of earlier thinking on the subject, but in confirmation of the more recent findings of Camill (1999a,b), the researchers discovered that aboveground biomass and decomposition "were more strongly controlled by local succession than regional climate." In other words, they determined that over a period of several years, natural changes in plant community composition generally "have stronger effects on carbon sequestration than do simple increases in temperature and aridity." In fact, their core-derived assessments of peat accumulation over the past two centuries demonstrated that rates of biological carbon sequestration can almost *double* following the melting of permafrost, in harmony with the findings of Robinson and Moore (2000) and Turetsky *et al.* (2000), who found rates of organic matter accumulation in other recently-thawed peatlands to have risen by 60-72%.

In another relevant study, Griffis and Rouse (2001) drew upon the findings of a number of experiments conducted over the past quarter-century at a subarctic sedge fen near Churchill, Manitoba, Canada, in order to develop an empirical model of net ecosystem CO<sub>2</sub> exchange there. The most fundamental finding of this endeavor was that "carbon acquisition is greatest during wet and warm conditions," such as is generally predicted for the world as a whole by today's most advanced climate models. However, since *regional* climate change predictions are not very dependable, the two scientists investigated the consequences of a 4°C increase in temperature accompanied by both a 30% increase *and decrease* in precipitation; and "in all cases," as they put it, "the equilibrium response showed substantial increases in carbon acquisition." One of the reasons behind this finding, as explained by Griffis and Rouse, is that "arctic ecosystems photosynthesize below their temperature optimum over the majority of the growing season," so that increasing temperatures enhance plant growth rates considerably more than they increase plant decay rates.

In summing up their findings, Griffis and Rouse reiterate the fact that "warm surface temperatures combined with wet soil conditions in the early growing season increase above ground biomass and carbon acquisition throughout the summer season." Indeed, they note that "wet *spring* conditions can lead to greater CO<sub>2</sub> acquisition through much of the growing period *even when drier conditions persist* [our italics]." They thus conclude that if climate

change plays out as described by current climate models, i.e., if the world becomes warmer and wetter, "northern wetlands should therefore become larger sinks for atmospheric CO<sub>2</sub>."

In a somewhat different type of study, Mauquoy *et al.* (2002) analyzed three cores obtained from a raised peat bog in the UK (Walton Moss) and a single core obtained from a similar bog in Denmark (Lille Vildmose) for macro- and micro-fossils (pollen), bulk density, loss on ignition, carbon/nitrogen ratios and humification, while they were <sup>14</sup>C dated by accelerator mass spectrometry. Among a variety of other things, it was determined, in their words, that "the lowest carbon accumulation values for the Walton Moss monoliths between ca. cal AD 1300 and 1800 and between ca. cal AD 1490 and 1580 for Lille Vildmose occurred during the course of Little Ice Age deteriorations," which finding they describe as being much the same as the observation "made by Oldfield *et al.* (1997) for a Swedish 'aapa' mire between ca. cal AD 1400 and 1800." They also report that "carbon accumulation before this, in the Medieval Warm Period, was higher, as was also the case following the Little Ice Age, as the earth transitioned to the Modern Warm Period. Consequently, whereas climate alarmists claim that warming will hasten the release of carbon from ancient peat bogs, these real-world data actually *demonstrate* that just the *opposite* is likely to be true.

In a somewhat similar study, but one that concentrated more on the role of nitrogen than of temperature, Turunen *et al.* (2004) derived recent (0-150 years) and long-term (2,000-10,000 years) apparent carbon accumulation rates for several ombrotrophic peatlands in eastern Canada with the help of <sup>210</sup>Pb- and <sup>14</sup>C-dating of soil-core materials. This work revealed that the average long-term apparent rate of C accumulation at 15 sites was  $19 \pm 8 \text{ g C m}^{-2} \text{ yr}^{-1}$ , which is comparable to long-term rates observed in Finnish bogs by Tolonen and Turunen (1996) and Turunen *et al.* (2002). Recent C accumulation rates at 23 sites, on the other hand, were much higher, averaging  $73 \pm 17 \text{ g C m}^{-2} \text{ yr}^{-1}$ , which results, in their words, are also "similar to results from Finland (Tolonen and Turunen, 1996; Pitkanen *et al.*, 1999) and for boreal *Sphagnum* dominated peat deposits in North America (Tolonen *et al.*, 1988; Wieder *et al.*, 1994; Turetsky *et al.*, 2000)." Noting that recent rates of C accumulation are "strikingly higher" than long-term rates, Turunen *et al.* suggested that increased N deposition "leads to larger rates of C and N accumulation in the bogs, as has been found in European forests (Kauppi *et al.*, 1992; Berg and Matzner, 1997), and could account for some of the missing C sink in the global C budget."

Returning to the role of temperature, Payette *et al.* (2004) quantified the main patterns of change in a subarctic peatland on the eastern coast of Canada's Hudson Bay, which were caused by permafrost decay between 1957 and 2003, based on detailed surveys conducted in 1973, 1983, 1993 and 2003. This work revealed there was continuous permafrost thawing throughout the period of observation, such that "about 18% of the initial frozen peatland surface was melted in 1957," while thereafter "accelerated thawing occurred with only 38%, 28% and 13% of the original frozen surface still remaining in 1983, 1993 and 2003, respectively." This process, in their words, was one of "terrestrialization" via the establishment of fen/bog vegetation, which nearly always results in either no net loss of carbon or actual carbon sequestration. As a result, Payette *et al.* concluded that "contrary to current expectations, the melting of permafrost caused by recent climate change does *not* [our italics]

transform the peatland to a carbon-source ecosystem." Instead, they say that "rapid terrestrialization exacerbates carbon-sink conditions and tends to balance the local carbon budget."

In a study of *experimental* warming of Icelandic plant communities designed to see if the warming of high-latitude tundra ecosystems will result in significant losses of species and reduced biodiversity, as climate alarmists often claim will occur, Jonsdottir *et al.* (2005) conducted a field experiment to learn how vegetation might respond to moderate warming at the low end of what is predicted by most climate models for a doubling of the air's CO<sub>2</sub> content. Specifically, they studied the effects of 3-5 years of modest surface warming (1-2°C) on two widespread but contrasting tundra plant communities, one of which was a nutrient-deficient and species-poor moss heath and the other of which was a species-rich dwarf shrub heath. At the conclusion of the study, no changes in community structure were detected in the moss heath. In the dwarf shrub heath, on the other hand, the number of deciduous and evergreen dwarf shrubs increased more than 50%, bryophytes decreased by 18% and canopy height increased by 100%, but with the researchers reporting that they "detected no changes in species richness or other diversity measures in either community and the abundance of lichens did not change."

Although Jonsdottir *et al.*'s study was a relatively short-term experiment as far as ecosystem studies go, its results are encouraging, as they indicate that a rise in temperature need not have a negative effect on the species diversity of high-latitude tundra ecosystems and that it may actually have a positive influence on plant growth, which consequences are a far, far cry from the ecological disasters that climate alarmists typically claim will occur in response to rising temperatures.

In a study that included an entirely new element of complexity, Cole *et al.* (2002) constructed 48 small microcosms from soil and litter they collected near the summit of Great Dun Fell, Cumbria, England. Subsequent to "defaunating" this material by reducing its temperature to -80°C for 24 hours, they thawed and inoculated it with native soil microbes, after which half of the microcosms were incubated in the dark at 12°C and half at 18°C for two weeks, in order to establish near-identical communities of the soils' natural complement of microflora in each microcosm. The former of these temperatures was chosen to represent mean August soil temperature at a depth of 10 cm at the site of soil collection, while the latter was picked to be "close to model predictions for soil warming that might result from a doubling of CO<sub>2</sub> in blanket peat environments."

Next, ten seedlings of *Festuca ovina*, an indigenous grass of blanket peat, were planted in each of the microcosms, while 100 enchytraeid worms were added to each of half of the mini-ecosystems, producing four experimental treatments: ambient temperature, ambient temperature plus enchytraeid worms, elevated temperature, and elevated temperature plus enchytraeid worms. Then, the 48 microcosms -- sufficient to destructively harvest three replicates of each treatment four different times throughout the course of the 64-day experiment -- were arranged in a fully randomized design and maintained at either 12 or 18°C

with alternating 12-hour light and dark periods, while being given distilled water every two days to maintain their original weights.

So what did the researchers learn? First of all, they found that elevated temperature reduced the ability of the enchytraeid worms to enhance the loss of carbon from the microcosms. At the normal ambient temperature, for example, the presence of the worms enhanced dissolved organic carbon (DOC) loss by 16%, while at the elevated temperature expected for a doubling of the air's CO<sub>2</sub> content they had no effect on DOC. In addition, Cole *et al.* note that "warming may cause drying at the soil surface, forcing enchytraeids to burrow to deeper subsurface horizons;" and since the worms are known to have little influence on soil carbon dynamics below a depth of about 4 cm (Cole *et al.*, 2000), the researchers concluded that this additional consequence of warming would further reduce the ability of enchytraeids to enhance carbon loss from blanket peatlands. In summing up their findings, therefore, Cole *et al.* concluded that "the soil biotic response to warming in this study was negative," in that it resulted in a reduced loss of carbon to the atmosphere.

But what about the effects of elevated CO<sub>2</sub> itself on the loss of DOC from soils? Freeman *et al.* (2004) note that riverine transport of DOC has increased markedly in many places throughout the world over the past few decades (Schindler *et al.*, 1997; Freeman *et al.*, 2001; Worrall *et al.*, 2003); and they suggest that this phenomenon may be related to the historical increase in the air's CO<sub>2</sub> content.

The researchers' first piece of evidence for this conclusion came from a 3-year study of monoliths (11-cm diameter x 20-cm deep cores) taken from three Welsh peatlands -- a *bog* that received nutrients solely from rainfall, a *fen* that gained more nutrients from surrounding soils and groundwater, and a *riparian peatland* that gained even more nutrients from nutrient-laden water transported from other terrestrial ecosystems via drainage streams -- which they exposed to either ambient air or air enriched with an extra 235 ppm of CO<sub>2</sub> within a solardome facility. This study revealed that the DOC released by monoliths from the three peatlands was significantly enhanced -- by 14% in the bog, 49% in the fen and 61% in the riparian peatland -- by the additional CO<sub>2</sub> to which they were exposed, which is the order of response one would expect from what we know about the stimulation of net primary productivity due to atmospheric CO<sub>2</sub> enrichment, i.e., it is low in the face of low soil nutrients, intermediate when soil nutrient concentrations are intermediate, and high when soil nutrients are present in abundance. Consequently, Freeman *et al.* concluded that the DOC increases they observed "were induced by increased primary production and DOC exudation from plants," which conclusion logically follows from their findings.

Nevertheless, and to further test their hypothesis, they followed the translocation of labeled <sup>13</sup>C through the plant-soil systems of the different peat monoliths for about two weeks after exposing them to ~99%-pure <sup>13</sup>CO<sub>2</sub> for a period of five hours. This exercise revealed that (1) the plants in the ambient-air and CO<sub>2</sub>-enriched treatments assimilated 22.9 and 35.8 mg of <sup>13</sup>C from the air, respectively, (2) the amount of DOC that was recovered from the leachate of the CO<sub>2</sub>-enriched monoliths was 0.6% of that assimilated, or 0.215 mg (35.8 mg x 0.006 = 0.215 mg),



and (3) the proportion of DOC in the soil solution of the CO<sub>2</sub>-enriched monoliths that was derived from recently assimilated CO<sub>2</sub> (the <sup>13</sup>C labeled CO<sub>2</sub>) was *ten times higher than that of the control*.

This latter observation suggests that the amount of DOC recovered from the leachate of the ambient-air monoliths was only about a tenth as much as that recovered from the leachate of the CO<sub>2</sub>-enriched monoliths, which puts the former amount at about 0.022 mg. Hence, *what really counts*, i.e., the *net* sequestration of <sup>13</sup>C experienced by the peat monoliths over the two-week period (which equals the amount that went into them minus the amount that went out), comes to 22.9 mg minus 0.022 mg = 22.878 mg for the ambient-air monoliths and 35.8 mg minus 0.215 mg = 35.585 mg for the CO<sub>2</sub>-enriched monoliths. In the end, therefore, even though the CO<sub>2</sub>-enriched monoliths lost ten times more <sup>13</sup>C via root exudation than did the ambient-air monoliths, they still sequestered about 55% more <sup>13</sup>C overall, primarily in living-plant tissues.

In light of this impressive array of pertinent findings, it would appear that continued increases in the air's CO<sub>2</sub> concentration and temperature would *not* result in massive losses of carbon from earth's peatlands. Quite to the contrary, these environmental changes -- if they persist -- would likely work together to *enhance* carbon capture by these particular ecosystems.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/c/carbonpeat.php>.

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## 8. SPECIES EXTINCTION

One of the more horriific claims of CO<sub>2</sub>-induced global warming is that increases in the air's temperature and CO<sub>2</sub> concentration will cause unprecedented plant and animal *extinctions*, both on land and in the waters of the world's oceans. The *truth*, however, is that there is precious little real-world *evidence* for such a claim. In fact, there is an abundance of *counter* evidence, which suggests that the vast majority of the predicted extinctions will *not* occur.

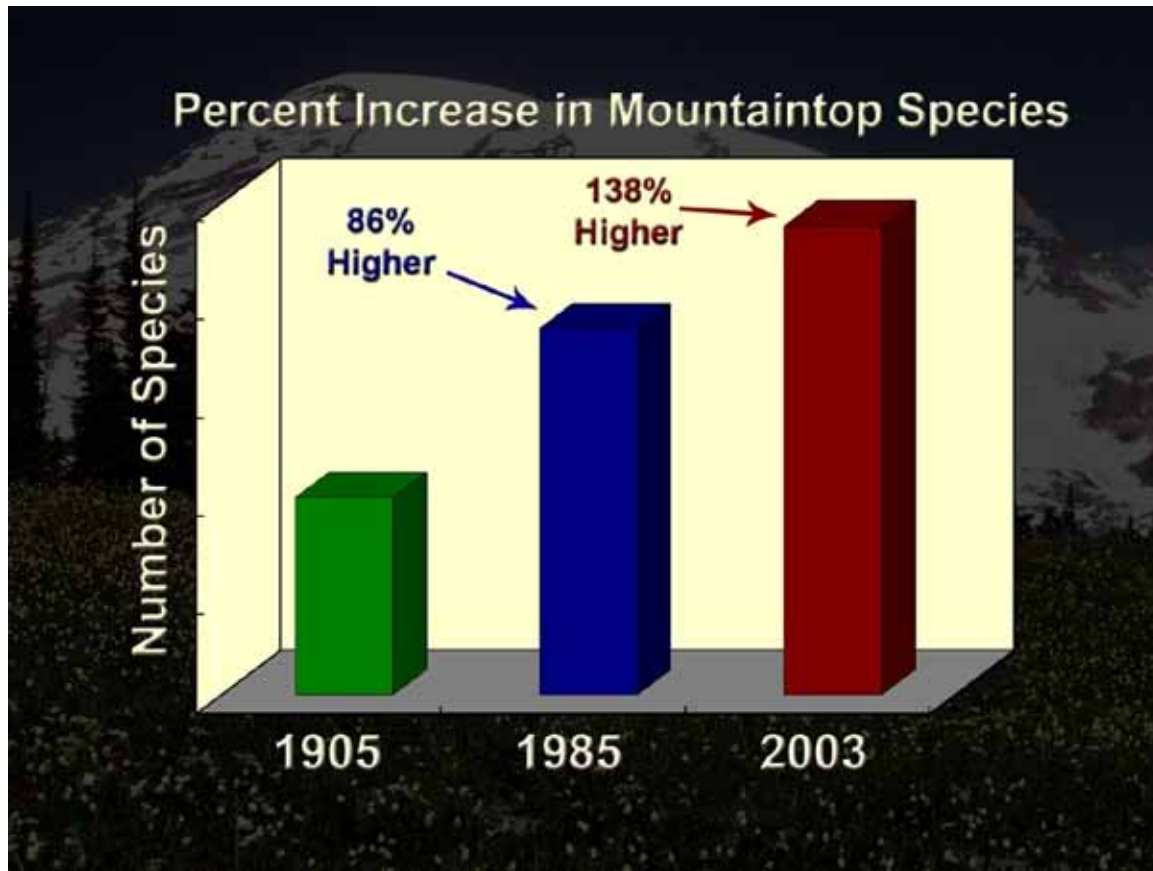
It is true that many plants and animals *do migrate* as climate changes; but in response to the global warming of the past century and projected *future* warming, another climate-alarmist icon, James Hansen, has presented testimony to a U.S. House of Representatives committee that included the claim that "polar species can be pushed off the planet, as they have no place else to go," and that "life in alpine regions ... is similarly in danger of being pushed off the planet."

This idea *sounds* logical enough, but is there any *evidence* that such things really happen in the real world? Do we know, for example, if any of earth's terrestrial plant and animal life has truly been "pushed off the planet" in response to what climate alarmists typically characterize as the *unprecedented warming of the 20<sup>th</sup> century*? We begin our study of the subject with a consideration of *terrestrial plants*.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/e/extinction.php>.

### **8.1. Terrestrial Plants**

A team of three researchers investigated this climate-alarmist scenario in July and August of 2003 by resurveying the floristic composition of the uppermost ten meters of ten mountain summits in the Swiss Alps (Walther *et al.*, 2005), applying the same methodology used in earlier surveys that were conducted there in 1905 (Rubel, 1912) and 1985 (Hofer, 1992). This analysis covered the bulk of the Little Ice Age-to-Current Warm Period transition; and it revealed that plants of many species had indeed marched up the sides of the mountains, as the earth in general -- and the Swiss Alps in particular -- had warmed. Of even *greater* significance, however, was the *fact* that *not a single mountain-top species* was "pushed off the planet." And as a result of that fact, between 1905 and 1985 the mean number of species observed on the ten mountaintops rose by 86%, while by 2003 it had risen by a whopping 138% (see figure below), providing, in the words of the researchers who conducted the work, "an enrichment of the overall summit plant diversity."



Another research team of four *different* individuals studied the same phenomenon on *twelve* mountaintops in the Swiss Alps (Holzinger *et al.* 2008), making complete inventories of vascular plant species that were present there in 2004, while following -- "as accurately as possible," in their words -- the same ascension paths used by other researchers in 1885, 1898, 1912, 1913 and 1958, after which they compared their findings with those of the earlier studies. By these means, they detected upward plant migration rates on the order of several meters per decade, which phenomenon increased vascular plant species richness at the mountains' summits by 11% per decade over the 120-year study period. This finding, in their words, "agrees well with other investigations from the Alps, where similar changes have been detected," and they cited, in this regard, four additional studies (Grabherr *et al.*, 1994; Pauli *et al.*, 2001; Camenisch, 2002; Walther, 2003).

Another pertinent study was conducted by a researcher who analyzed altitudinal shifts in the ranges of alpine and subalpine plants in the mountains of west-central *Sweden* (Kullman, 2002), where air temperature had risen approximately 1°C over the past hundred years. This work revealed that since the early 20<sup>th</sup> century, alpine and subalpine plants had migrated upslope by an average of 200 m. Most importantly, it also indicated, according to the scientist who did the work, that "no species have yet become extinct from the highest elevations," which finding was said by the researcher to "converge with observations in other high-mountain regions worldwide," in support of which statement five *more* new studies were cited (Keller *et al.*,

2000; Kullman, 2002; Klanderud and Birks, 2003; Virtanen *et al.*, 2003; Lacoul and Freedman, 2006).

In light of these many *real-world findings*, it should be abundantly clear that even the highly-hyped warming of the past century -- which climate alarmists claim was *unprecedented* over the past one to two *millennia* -- likely did not "push" any upward-migrating plants "off the planet" at the tops of its mountains. Hence, one of the most highly promoted *hypothetical scenarios* of the IPCC is clearly seen to be just that -- a *hypothetical scenario*.

But what about terrestrial *animals*? And what about pushing them towards earth's *poles* rather than its mountaintops?

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## **8.2. Terrestrial Animals**

A good place to begin a review of this subject is a study conducted by a group of thirteen researchers that was published in the British journal *Nature* back in 1999 (Parmesan *et al.*, 1999). These scientists analyzed changes in the ranges of non-migratory *butterfly* species over the past century, whose northern boundaries were located in northern Europe and whose southern boundaries were located in southern Europe or northern Africa. This work revealed, as stated by the researchers involved in the study, that “nearly all northward [range] shifts involved extensions at the northern boundary with the southern boundary remaining stable.”

This type of behavior is *precisely* what we would expect to see given the *fact* that increases in atmospheric CO<sub>2</sub> concentration tend to reduce the adverse effects of heat stress in plants and actually induce an upward shift in the temperature at which they function optimally (Idso and Idso, 1994; Idso, 1995; Cowling and Sykes, 1999). That is to say, plants growing in CO<sub>2</sub>-enriched air actually *prefer* warmer temperatures; and this phenomenon tends to counter the impetus for poleward migration at the warm edge of a plant’s range, while warming provides an *opportunity* for significant poleward expansion at the cold edge of its range. Thus, it is possible that the observed *increases* in butterfly ranges over the past century of concomitant warming and rising atmospheric CO<sub>2</sub> concentration are related to matching changes in the ranges of the plants upon which the butterflies depend for food and shelter.

Or ... the range expansions could be due to some suite of more complex phenomena, possibly even some direct physiological effects of rising temperature and atmospheric CO<sub>2</sub> concentration on the butterflies themselves. In any event, 20<sup>th</sup>-century warming in Europe has actually been *beneficial* for the continent's butterflies; for the scientists who conducted the work report that "nearly all northward shifts involved extensions at the northern boundary with the southern boundary remaining stable," so that "most species effectively expanded the size of their range when shifting northwards," which range expansions would clearly *decrease* their chances of extinction in a warming world.

In an analogous study that was also published in the journal *Nature* in 1999, two researchers analyzed the geographical distributions of a number of British *bird* species over a 20-year period of global warming, looking for climate-induced changes in their breeding ranges between 1970 and 1990 (Thomas and Lennon, 1999). Their work revealed that the northern margins of southerly species' breeding ranges shifted northward by an average of 19 km over this period; while the mean location of the southern margins of northerly species' breeding ranges shifted *not at all*, which observations are again indicative of *expanding* ranges and a propensity for birds -- like butterflies -- to become more *resistant* to extinction in a warming world.

Still more support for this concept was provided by a 2004 study of the birds of Finland (Brommer, 2004), which were categorized as either *northerly* (34 species) or *southerly* (116 species). In this analysis the researcher quantified changes in their range margins and distributions from two atlases of breeding birds, one covering the period 1974-79 and one covering the period 1986-89, in an attempt to determine how the two groups of species responded to what he called "the period of the earth's most rapid climate warming in the last 10,000 years." Once again, it was determined that the southerly group of bird species experienced a mean poleward advancement of their northern range boundaries of 18.8 km over the 12-year period of supposedly unprecedented warming. The *southern* range boundaries of the *northerly* species, on the other hand, were essentially unmoved, leading once again to range *expansions* that should have rendered the Finnish birds *less* subject to extinction than they were before the warming.

Similar results were also obtained in a study of changes in the northern and southern range boundaries of 37 non-migratory British *dragonfly* and *damselfly* species between the two 10-year periods 1960-70 and 1985-95 (Hickling *et al.*, 2005). In this case, all but two of the 37 species *increased* the sizes of their ranges between the two 10-year periods, with the researchers reporting that "species are shifting northwards faster at their northern range margin than at their southern range margin," and concluding that "this could suggest that species at their southern range margins are less constrained by climate than by other factors," which surely appears to be the case.

In one final land animal study that harkens back to James Hansen's idea of species being "pushed off the planet" by warming at the tops of mountains, three researchers studied four unconnected populations of a small live-bearing *lizard* that lives in peat bogs and heath lands



scattered across Europe and Asia, concentrating on a small region near the top of a mountain in southeast France at the southern limit of the species' range (Chamaille-Jammes *et al.*, 2006). There, from 1984 to 2001, they monitored a number of life-history traits of the populations, including body size, reproductive characteristics and survival rates, during which time local air temperatures rose by approximately 2.2°C. In doing so, they observed that individual body size increased dramatically in all four populations over the 18-year study period in all age classes and, in the words of the researchers, "appeared related to a concomitant increase in temperature experienced during the first month of life." As a result, since fecundity is strongly dependent on female body size, they found that "clutch size and total reproductive output also increased." In addition, they learned that "adult survival was positively related to May temperature."

In discussing their findings, the French researchers say that since *all fitness components investigated responded positively to the increase in temperature*, "it might be concluded that the common lizard has been advantaged by the shift in temperature." This finding, as they describe it, stands in stark contrast to what they call the "habitat-based prediction that these populations located close to mountain tops on the southern margin of the species range should be unable to cope with the alteration of their habitat." Hence, they conclude that "to achieve a better prediction of a species persistence, one will probably need to combine both habitat and individual-based approaches," noting, however, that *individual responses*, such as those documented in their study (which were all positive), represent "the ultimate driver of a species response to climate change."

Coming down from the mountaintop and peering into the world's oceans -- where climate alarmists additionally contend that global warming is causing corals to lose their symbiotic algae and experience deadly *coral bleaching* -- we investigate *this* phenomenon, as well as *another* extinction scenario that they promote simultaneously.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/r/rangeexpandimals.php>.

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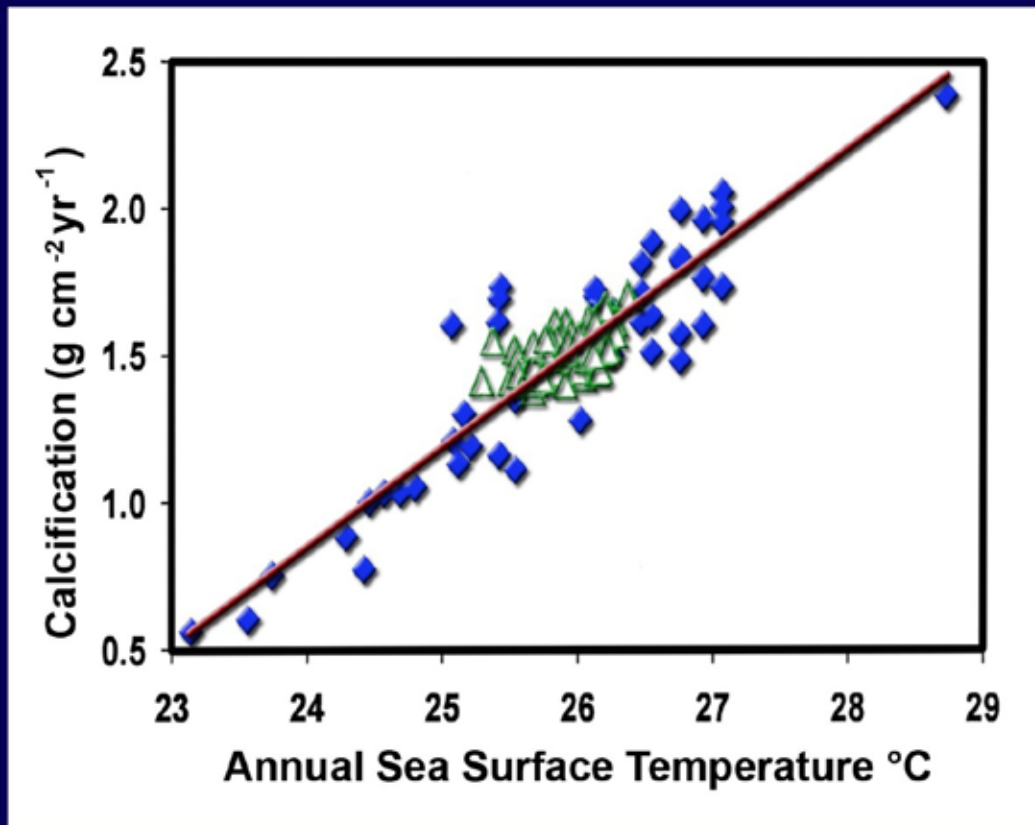
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### **8.3. Coral Reefs**

For some time now, it has been claimed that the ongoing rise in the atmosphere's CO<sub>2</sub> concentration is raising havoc with earth's corals, as well as numerous other calcifying marine organisms, by *acidifying the world's oceans* and thereby lowering the calcium carbonate saturation state of seawater, which -- climate alarmists claim -- makes it much more difficult for such creatures to produce their calcium carbonate skeletons (Orr *et al.*, 2005). However, there is no compelling reason to believe that calcifying marine life will be significantly harmed, much less *destroyed*, by this phenomenon; for the CO<sub>2</sub>-induced acidification hypothesis, along with its associated deadly consequences, is based almost *solely* upon *physical-chemical* effects, while it *totally ignores* some important *biological* processes.

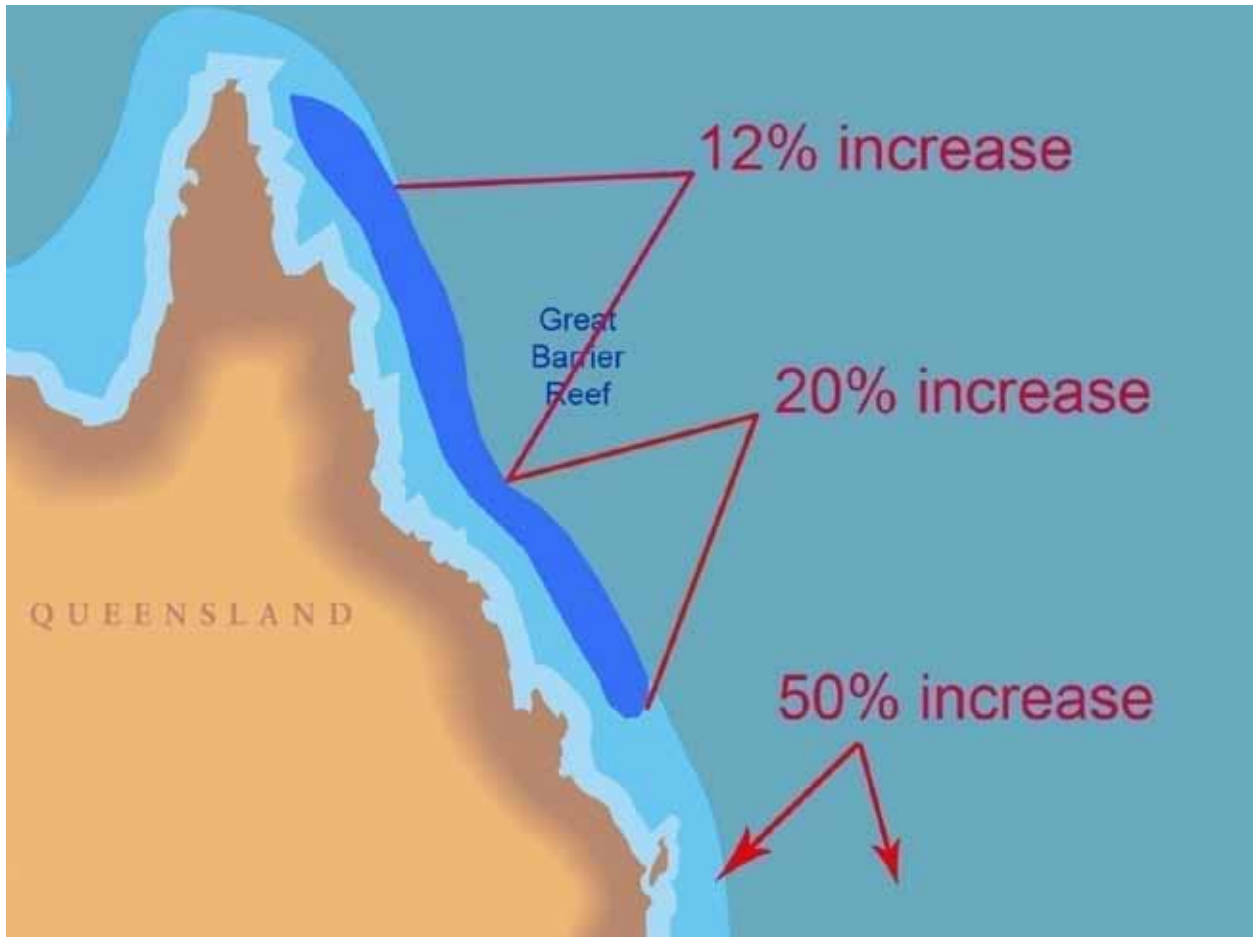
So what's the story here? Is there any real-world evidence that can be cited in support of these strident claims? Climate alarmists certainly make it *appear* such is the case; but a little scientific sleuthing reveals nothing of substance in this regard. In fact, it seems to suggest just the *opposite*.

In a study of colonies of *Porites* coral scattered throughout Australia's Great Barrier Reef (Lough and Barnes, 2000) -- which benefited from additional data obtained from Hawaii (Grigg, 1981; Grigg, 1997) and Thailand (Scoffin *et al.*, 1992) that significantly extended the sea surface temperature range investigated -- calcification rates were found to be linearly related to temperature, with a 1°C increase in average annual sea surface temperature actually *increasing* average annual calcification rate by 0.33 g per cm<sup>2</sup> per year.



Noting that their results allowed them to make an “assessment of possible impacts of global climate change on coral reef ecosystems,” the pair of researchers who conducted the work determined that between the two 50-year periods 1880 through 1929 and 1930 through 1979, there was an approximate 4% *increase* in calcification rate, which result is radically different from the 6-14% *decrease* suggested to result from CO<sub>2</sub>-induced ocean acidification by a study based primarily upon *theoretical calculations* (Kleypas *et al.*, 1999), as opposed to the host of *real-world observations* acquired from Australia, Hawaii and Thailand.

Even *more* stunning was the two researchers’ discovery that between the two 20-year periods 1903 through 1922 and 1979 through 1998, the warming-induced *increase* in coral calcification was about 12% in the *central* Great Barrier Reef, about 20% in the *southern* Great Barrier Reef, and as much as 50% to the *south* of the Great Barrier Reef. In light of these actual calcification rate *measurements*, therefore, and in stark contrast to the mere *contentions* of Al Gore and James Hansen, the two researchers concluded that coral calcification rates “may have already significantly increased along the Great Barrier Reef in response to global climate change.”



Two other scientists investigated the subject using data obtained from a massive *Porites* coral on the French Polynesian island of Moorea (Bessat and Buigues, 2001). This effort indicated that a 1°C increase in water temperature increased coral calcification rate by 4.5%, leading the pair of scientists to similarly state that “instead of a 6-14% decline in calcification over the past 100 years, calcification has increased.”

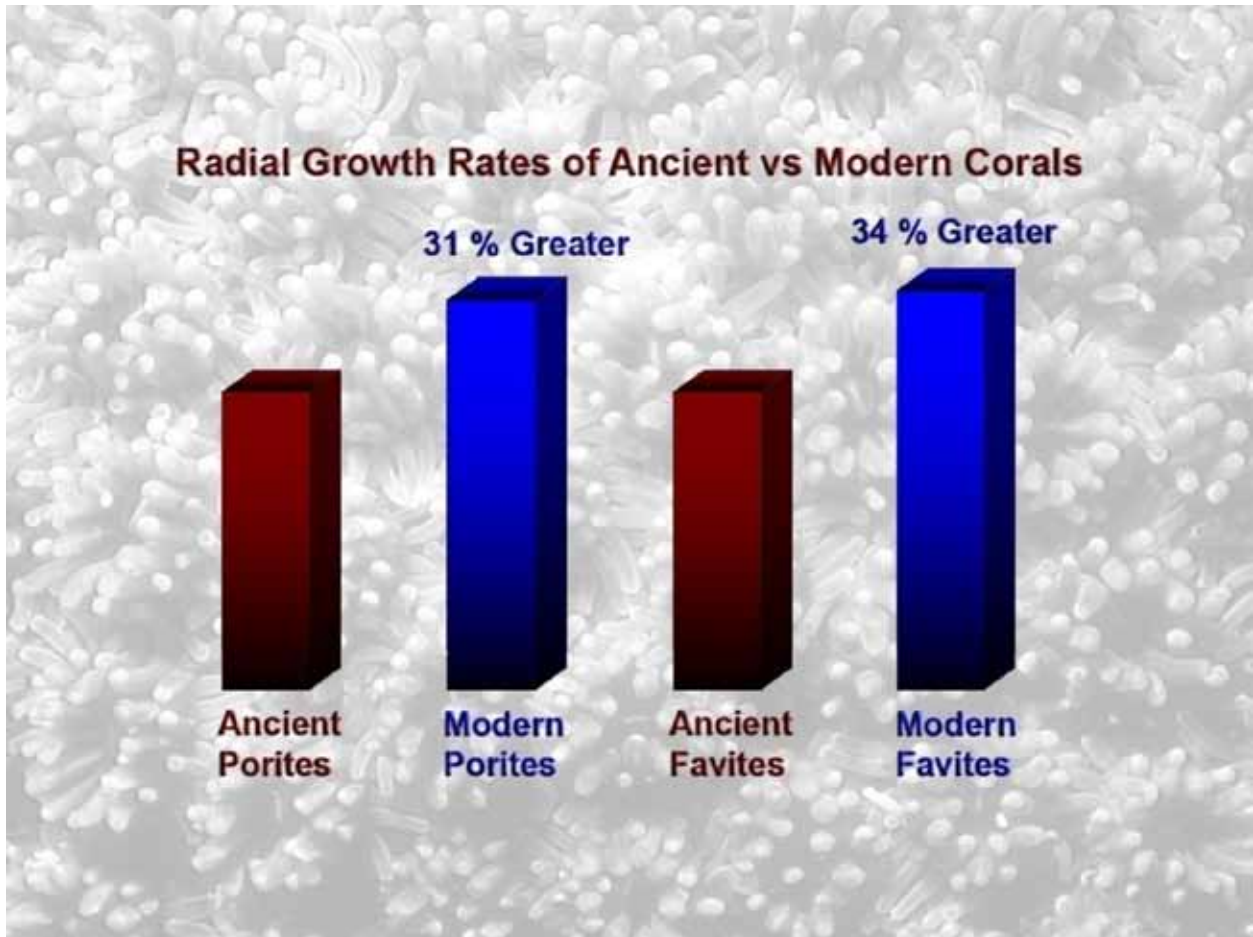
At about the same time, yet *another* scientist (Carricart-Ganivet, 2004) developed a relationship between coral calcification rate and annual average sea surface temperature, based on data collected from colonies of a different reef-building coral at twelve locations in the Gulf of Mexico and the Caribbean Sea. This work revealed that the mean calcification rate in the Gulf of Mexico rose by 0.55 g per cm<sup>2</sup> per year for each 1°C temperature increase, while in the Caribbean Sea it rose by 0.58 g per cm<sup>2</sup> per year, which result was nearly *twice as great* as that obtained in the original *Porites* study we discussed. Finally, after pooling these data with data obtained from still other species of coral living off the coasts of Belize (Graus and Macintyre, 1982), the U.S. Virgin Islands (Dodge and Brass, 1984), and the Netherlands Antilles (Bosscher, 1993), an all-inclusive relationship of about 0.5 g of calcification per cm<sup>2</sup> per year for each 1°C increase in annual average sea surface temperature was obtained.

To these papers we could add many others (Clausen and Roth, 1975; Coles and Jokiel, 1977; Kajiwara *et al.*, 1995; Nie *et al.*, 1997; Reynaud-Vaganay *et al.*, 1999; Reynaud *et al.*, 2004) that *also* depict increasing rates of coral calcification in the face of rising temperatures and atmospheric CO<sub>2</sub> concentrations. As for *why* this is the way earth's corals respond, one research group (McNeil *et al.*, 2004) has said that "observed increases in coral reef calcification with ocean warming are most likely due to an enhancement in coral metabolism and/or increases in photosynthetic rates of their symbiotic algae," as we have consistently stated on our website when noting, over and over, that coral calcification is a *biologically-driven* process that can overcome physical-chemical limitations, which in the *absence of life* would appear to be insurmountable.

One more reason for not believing the ongoing rise in the air's CO<sub>2</sub> content will lead to reduced oceanic pH in the vicinity of the world's coral reefs and thereby lower their calcification rates, is that the same phenomenon that powers the twin processes of coral calcification and phytoplanktonic growth -- namely, *photosynthesis* -- tends to *increase* the pH of marine waters (Gnaiger *et al.*, 1978; Santhanam *et al.*, 1994; Brussaard *et al.*, 1996; Lindholm and Nummelin, 1999; Macedo *et al.*, 2001; Hansen, 2002). And this phenomenon has been shown to have the ability to dramatically increase the pH of the world's marine bays, lagoons and tidal pools (Hansen, 2002 (Gnaiger *et al.*, 1978; Santhanam *et al.*, 1994; Macedo *et al.*, 2001; Hansen, 2002), as well as significantly enhance the surface-water pH of oceanic areas as large as the North Sea (Brussaard *et al.*, 1996).

In one additional study devoted to corals that involves a much longer period of time than all of the others we have discussed, another research team (Crabbe *et al.*, 2006) determined the original growth rates of long-dead Quaternary corals found in limestone deposits of islands in the Wakatobi Marine National Park of Indonesia, after which they compared them to the growth rates of present-day corals of the same genera living in the same area.

Their work revealed that the Quaternary corals grew "in a comparable environment to modern reefs" -- except, of course, for the air's CO<sub>2</sub> concentration, which is currently higher than it has been at any other time throughout the entire Quaternary, which spans the past 1.8 million years. Most interestingly, their measurements indicated that the radial growth rates of the modern corals were 31% *greater* than those of their ancient predecessors in the case of *Porites* species, and 34% greater in the case of *Favites* species.



Clearly, the *net impact* of 20<sup>th</sup>-century increases in atmospheric CO<sub>2</sub> and temperature has not been anywhere near as catastrophically disruptive to earth's corals as climate-alarmist dogma suggests it should have been. Quite to the contrary, the temperature and CO<sub>2</sub> increases appear to not have been hurtful *at all*. In fact, they actually appear to have been *helpful*. But what about *other* calcifying marine organisms? Have they been harmed in any way?

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/c/calcification.php>.

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#### 8.4. Other Calcifying Sea Life

Some insight into this subject was recently provided by an international team of thirteen researchers (Iglesias-Rodriguez *et al.*, 2008), who bubbled air of a number of different atmospheric CO<sub>2</sub> concentrations through culture media containing the phytoplanktonic coccolithophore species *Emiliana huxleyi*, while determining the amounts of particulate organic and inorganic carbon they produced. In addition, they determined the real-world change in average coccolithophore mass over the past 220 years in the subpolar North Atlantic Ocean, based on data obtained from a sediment core, over which period of time the atmosphere's CO<sub>2</sub> concentration rose by approximately 90 ppm and the earth emerged from the frigid depths of the Little Ice Age to experience the supposedly unprecedented high temperatures of the Current Warm Period. So what did they find?

What they found was an approximate *doubling* of both particulate organic and inorganic carbon between the culture media in equilibrium with air of today's CO<sub>2</sub> concentration and the culture media in equilibrium with air of 750 ppm CO<sub>2</sub>. In addition, they say the field evidence they obtained from the deep-ocean sediment core they studied "is consistent with these laboratory conclusions," and that it indicates that "over the past 220 years there has been a 40% increase in average coccolith mass."

Focusing more on the *future*, a second independent team of seven scientists (Feng *et al.*, 2008) studied *Emiliana huxleyi* coccoliths that they isolated from the Sargasso Sea, and which they grew in semi-continuous culture media at low and high light intensities, low and high temperatures (20 and 24°C), and low and high CO<sub>2</sub> concentrations (375 and 750 ppm). This work revealed that in the *low-light* environment, the maximum photosynthetic rate was lowest in the low-temperature, low-CO<sub>2</sub> or *ambient* treatment, but was increased by 55% by *elevated temperature alone* and by 95% by *elevated CO<sub>2</sub> alone*, while in the high-temperature, high-CO<sub>2</sub> or *greenhouse* treatment it was increased by 150% relative to the *ambient* treatment.

Likewise, in the *high-light* environment, there were maximum photosynthetic rate increases of 58%, 67% and 92% for the *elevated temperature alone*, *elevated CO<sub>2</sub> alone* and *greenhouse* treatments, respectively. Consequently, the researchers concluded, in their words, that "future trends of CO<sub>2</sub> enrichment, sea-surface warming and exposure to higher mean irradiances from intensified stratification will have a large influence on the growth of *Emiliana huxleyi*." And, of course, that "large influence" will be *positive*, and tremendously so.

Clearly, climate-alarmist claims of impending species extinctions due to increases in both temperature and atmospheric CO<sub>2</sub> concentration are not only *not supported* by real-world evidence, they are actually *refuted* by it. But there is one additional phenomenon that we need to discuss that may also play a vital role in how life on earth would likely respond to any rapid increase in temperature that might possibly occur in the future for *whatever* reason, and that is the phenomenon of *rapid evolutionary change* – the ability of plants and animals to actually evolve in response to dramatic shifts in climate.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/c/calcificationother.php>.

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### **8.5. Rapid Evolutionary Change**

One example of rapid evolutionary change is illustrated in a paper published in 2007 by a group of scientists (Skelly *et al.*, 2007) from the United States, Canada and Australia, who critiqued the so-called *climate-envelope approach* to predicting extinctions -- which is highly regarded by Al Gore and James Hansen -- citing as their primary reason for doing so the fact that this approach "implicitly assumes that species cannot evolve in response to changing climate." But, as they correctly point out, "many examples of contemporary evolution in response to climate change exist," such as populations of a frog they had studied that had "undergone localized evolution in thermal tolerance (Skelly and Freidenburg, 2000), temperature-specific development rate (Skelly, 2004), and thermal preference (Freidenburg and Skelly, 2004)," *in less than 40 years*. Similarly, they report that "laboratory studies of insects show that thermal tolerance can change markedly after as few as 10 generations (Good, 1993)."

Adding that "studies of microevolution in plants show substantial trait evolution in response to climate manipulations (Bone and Farres, 2001)," the researchers further noted that "collectively, these findings show that genetic variation for traits related to thermal performance is common and evolutionary response to changing climate has been the typical finding in experimental and observational studies (Hendry and Kinnison, 1999; Kinnison and Hendry, 2001)."

Although evolution will obviously be slower in the cases of long-lived trees and large mammals, where long generation times are the norm, the scientists say that the case for rapid evolutionary responses among many other species "has grown much stronger," citing, in this regard, the work of six other groups of researchers comprised of two dozen different individuals (Stockwell *et al.*, 2003; Berteaux *et al.*, 2004; Hairston *et al.*, 2005; Bradshaw and Holzapfel, 2006; Schwartz *et al.*, 2006; Urban *et al.*, 2007). As a result, they write that "on the basis of the present knowledge of genetic variation in performance traits and species' capacity for evolutionary response, it can be concluded that evolutionary change will often occur concomitantly with changes in climate as well as other environmental changes (Stockwell *et al.*, 2003; Grant and Grant, 2002; Balanya *et al.*, 2006; Jump *et al.*, 2006; Pelletier *et al.*, 2007)."

Much the same conclusion has been reached by still other groups of scientists. In a study of the field mustard plant that was also published in 2007, for example, a group of three researchers (Franks *et al.*, 2007) found evidence for what they describe as “a rapid, adaptive evolutionary shift in flowering phenology after a climatic fluctuation,” which finding, in their words, “adds to the growing evidence that evolution is not always a slow, gradual process but can occur on contemporary time scales in natural populations.”

Likewise, another group of researchers who published in 2007 (Rae *et al.*, 2007) -- who worked with hybrids of two *Populus* tree species -- obtained results which, as they phrased it, “quantify and identify genetic variation in response to elevated CO<sub>2</sub> and provide an insight into genomic response to the changing environment.” In regard to these findings, they wrote that they “should lead to an understanding of microevolutionary response to elevated CO<sub>2</sub> ... and aid future plant breeding and selection,” noting that various research groups have already identified numerous genes that appear sensitive to elevated CO<sub>2</sub> (Gupta *et al.*, 2005; Taylor *et al.*, 2005; Ainsworth *et al.*, 2006; Rae *et al.*, 2006).

Life in the sea, in this regard, is no different from life on land. In another study published in 2007, for example, a team of four marine biologists (Van Doorslaer *et al.*, 2007) conducted an experiment with a species of zooplankton in which they say they “were able to demonstrate a rapid microevolutionary response (within 1 year) in survival, age at reproduction and offspring number to elevated temperatures,” and they state that “these responses may allow the species to maintain itself under the forecasted global warming scenarios,” noting that what they learned “strongly indicates rapid microevolution of the ability to cope with higher temperatures.” And, of course, other studies have produced analogous results with respect to increases in temperature on corals (Kumaraguru *et al.*, 2003; Willis *et al.*, 2006) and increases in CO<sub>2</sub> on freshwater microalgae (Collins *et al.*, 2006).

Additional information on this topic, including reviews of newer publications as they become available, can be found at [http://www.co2science.org/subject/e/subject\\_e.php](http://www.co2science.org/subject/e/subject_e.php) under the subheading Evolution.

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## **8.6. Conclusion**

Climate alarmists *claim* that as the world warms in response to the ongoing rise in the air's CO<sub>2</sub> content, many plant and animal species will be driven to extinction because they will not be

able to migrate either poleward in latitude or upward in elevation fast enough to escape the stress imposed by the rising temperatures. Real-world *observations*, on the other hand, suggest just the *opposite*.

With respect to plants, as long as the atmosphere's CO<sub>2</sub> concentration rises in tandem with its temperature, most of them will not "feel the heat," as their physiology will change in ways that make them better adapted to warmer conditions. Hence, although earth's plants will likely spread poleward in latitude and upward in elevation at the cold-limited boundaries of their ranges in response to a warming-induced opportunity to do so, their heat-limited boundaries will probably remain pretty much as they are now or shift only slightly. Consequently, in a world of rising atmospheric CO<sub>2</sub> concentration, the ranges of most of earth's plants will likely *expand* if the planet continues to warm, making terrestrial plant extinctions even *less* likely than they are currently.

As for land animals, they appear to react in much the same way. In response to increases in atmospheric temperature and CO<sub>2</sub> concentration, they tend to migrate poleward and upward, where cold temperatures prevented them from going in the past, as they follow earth's plants, while the heat-limited boundaries of their ranges are often little affected, allowing them to also expand their ranges.

With respect to marine life -- and especially that of calcifying organisms such as corals and coccolithophores -- neither increases in *temperature*, nor increases in atmospheric *CO<sub>2</sub> concentration*, nor increases in both of them *together*, have had any ill effects on the important processes of calcification and growth. In fact, out in the real world of nature, these processes have actually responded *positively* to the supposedly unprecedented concomitant increases in these "twin evils" of the radical environmentalist movement.

So where does all of this information leave us? On the one hand, a goodly portion of earth's plants and animals should actually *expand* their ranges and gain a *stronger* foothold on the planet, as the atmosphere's temperature and CO<sub>2</sub> concentration continue to rise. On the other hand, if the air's CO<sub>2</sub> content were suddenly to *stop* increasing, the biosphere could find itself facing a significant challenge, as the world's plants would cease acquiring the extra physiological protection against heat stress that is afforded them by rising atmospheric CO<sub>2</sub> concentrations. Consequently, the end result of curtailing humanity's CO<sub>2</sub> emissions might well be just the *opposite* of what many people are hoping to accomplish by encouraging that policy; and many species of plants and animals might actually be *driven* to extinction, rather than being *saved* from such a fate. We have got to realize that rising atmospheric CO<sub>2</sub> concentrations are *not* the *bane of the biosphere*, but a *boon* to the planet's many lifeforms.

## 9. HUMAN HEALTH

The idea that CO<sub>2</sub>-induced global warming is responsible for increases in a host of human maladies has become incorrectly entrenched in popular culture. Hardly a heat wave passes, for example, but what many are quick to blame global warming for any excess deaths that may have been associated with it. However, if the truth were told, and all of the scientific literature were justly examined, one would find that global warming will likely do just the *opposite* and actually *reduce* the number of lives lost to extreme thermal conditions, as many more people die from unseasonably cold temperatures than from excessive warmth. What is more research has shown that there are also a number of *positive* effects of atmospheric CO<sub>2</sub> enrichment that tend to *enhance* people's quality of life, but about which little is spoken. In this next chapter we investigate such phenomena, beginning with a discussion on temperature-induced mortality.

### **9.1. Temperature-Induced Mortality**

Which is more deadly ... *heat* or *cold*? ... *rising* temperatures or *falling* temperatures? The world's climate alarmists say that *warming* is the primary danger ... and that it should be avoided at essentially *all costs*. Real-world *data*, however, suggest otherwise.

The *positive* health effects of *heat* have been well-documented over the past quarter-century. The early studies of Bull (1973) and Bull and Morton (1975a,b) in England and Wales, for example, demonstrated that even normal changes in temperature are typically associated with *inverse* changes in death rates, especially in older subjects. That is, when temperatures *rise*, death rates *fall*, while when temperatures *fall*, death rates *rise*. Also, Bull and Morton (1978) report "there is a close association between temperature and death rates from *most* diseases at *all* temperatures," and they say it is "very likely that changes in external temperature *cause* changes in death rates."

Another interesting finding of the study of Bull and Morton (1978) relates to *extremes* of heat and cold. They report that at the lower end of the temperature range, "there are more deaths the longer the 'run of days,' while at the higher end of the temperature range the reverse is true," i.e., "the longer the 'run' the fewer the deaths," suggesting that people adapt more readily to extreme heat than extreme cold. Among the various diseases that exhibit these relationships, they make particular note of "atherosclerotic diseases (strokes, ischemic heart disease, hypertension and diabetes)" and "respiratory diseases," which we will consider in more depth in that order.

Additional information on this topic, including reviews on the health effects of CO<sub>2</sub> not discussed here, can be found at [http://www.co2science.org/subject/h/subject\\_h.php](http://www.co2science.org/subject/h/subject_h.php) under the heading Health Effects

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### 9.1.1. Cardiovascular Diseases

A good place to begin a review of temperature-related mortality is a *cold* location ... like *Siberia*. Hence, we start with the study of Feigin *et al.* (2000), who examined the relationship between stroke occurrence and weather parameters in the Russian city of Novosibirsk, which has one of the highest incidence rates of stroke in the entire world.

Analyzing the health records of 2208 patients with a sex and age distribution similar to that of the whole of Russia over the period 1982-93, Feigin *et al.* found a statistically significant association between stroke occurrence and low ambient temperature. For ischemic stroke (IS), which accounted for 87% of all strokes recorded, they report that *the risk of IS occurrence on days with low ambient temperature is 32% higher than that on days with high ambient temperature*. Hence, they suggested the implementation of "preventive measures ... such as avoiding low temperature."

Hong *et al.* (2003) observed much the same thing in Incheon, Korea, over the period January 1998 to December 2000, reporting that "decreased ambient temperature was associated with risk of acute ischemic stroke," with the strongest effect being seen on the day after exposure to cold weather, further noting that "even a moderate decrease in temperature can increase the risk of ischemic stroke." In addition, they note that "risk estimates associated with decreased temperature were greater in winter than in the summer," which suggests, in their words, that "low temperatures as well as temperature changes are associated with the onset of ischemic stroke."

Nafstad *et al.* (2001) studied another cold place: Oslo, Norway. Thanks to Norwegian law, which requires all deaths to be examined by a physician who diagnoses cause and reports it on the death certificate, they were able to examine the effects of temperature on mortality due to all forms of cardiovascular disease for citizens of the country's capital over the period 1990 to 1995. Their analysis showed that *the average daily number of cardiovascular-related deaths was 15% higher in the winter months (October-March) than in the summer months (April-*



September), leading them to also conclude that "a milder climate would lead to a substantial reduction in average daily number of deaths."

To see if these relationships between cold temperatures and cardiovascular *mortality* are preceded by an even more general health-temperature relationship, Hajat and Haines (2002) set out to determine if mere cardiovascular-related *doctor visits* by the elderly bore a similar relationship to cold temperatures. Based on data obtained for registered patients aged 65 and older from several London, England practices between January 1992 and September 1995, they did indeed find that the mean number of general practitioner consultations was higher in the cool-season months (October-March) than in the warm-season months (April-September) *for all cardiovascular diseases*.

Of course, one might say, such findings are only to be expected in *cold* climates. What about *warm* climates, where summer maximum temperatures are often extreme, but summer minimum temperatures are typically mild?

In Israel, research conducted by Green *et al.* (1994) revealed that between 1976 and 1985, *mortality from cardiovascular disease was higher by 50% in mid-winter than in mid-summer, both in men and women and in different age groups*, in spite of the fact that summer temperatures in the Negev, where much of the work was conducted, often exceed 30°C, while winter temperatures typically do not drop below 10°C. These findings are also substantiated by other Israeli studies that have been reviewed by Behar (2000), who states that "most of the recent papers on this topic have concluded that a peak of sudden cardiac death, acute myocardial infarction and other cardiovascular conditions is usually observed in low temperature weather during winter."

Evidence of a seasonal variation in cardiac-related mortality has additionally been noted in the relatively mild climate of southern California in the United States. In a study of all 222,265 death certificates issued by Los Angeles County for deaths caused by coronary artery disease from 1985 through 1996, Kloner *et al.* (1999) found that *death rates in December and January were 33% higher than those observed in the period June through September*. Likewise, based on a study of the Hunter region of New South Wales, Australia, that covered the period 1 July 1985 to 30 June 1990, Enquesslassie *et al.* (1993) determined that "fatal coronary events and non-fatal definite myocardial infarction were 20-40% more common in winter and spring than at other times of year," while with respect to *daily* temperature effects, they found that "rate ratios for deaths were significantly higher for low temperatures," noting that "on cold days coronary deaths were up to 40% more likely to occur than at moderate temperatures."

In a study of both "hot" and "cold" cities in the United States -- where Atlanta, Georgia; Birmingham, Alabama; and Houston, Texas comprised the "hot" group, and where Canton, Ohio; Chicago, Illinois; Colorado Springs, Colorado; Detroit, Michigan; Minneapolis-St. Paul, Minnesota; New Haven, Connecticut; Pittsburgh, Pennsylvania; and Seattle and Spokane, Washington comprised the "cold" group -- Braga *et al.* (2002) determined both the acute effects and lagged influence of temperature on cardiovascular-related deaths. Their research

revealed that in the hot cities, neither hot nor cold temperatures had much impact on mortality related to cardiovascular disease (CVD). In the cold cities, on the other hand, they report that both high and low temperatures were associated with increased CVD deaths, with the effect of cold temperatures persisting for days but the effect of high temperatures restricted to the day of the death or the day before. Of particular interest was the finding that *for all CVD deaths the hot-day effect was five times smaller than the cold-day effect*. In addition, the hot-day effect included some "harvesting," where the authors observed a deficit of deaths a few days later, which they did not observe for the cold-day effect.

Finally, in a study conducted in Sao Paulo, Brazil, based on data collected over the period 1991-1994, Gouveia *et al.* (2003) determined that the number of cardiovascular-related deaths in adults (15-64 years of age) increased by 2.6% for each 1°C decrease in temperature below 20°C, while *there was no evidence for any heat-induced deaths due to temperatures rising above 20°C*. In the elderly (65 years of age and above), however, a 1°C warming above 20°C led to a 2% increase in deaths; but a 1°C cooling below 20°C led to a 6.3% increase in deaths, or *more than three times as many cardiovascular-related deaths due to cooling than to warming in the elderly*.

The results of these several studies, and several others for Australia (Enquesselassie *et al.*, 1993), Brazil (Sharovsky *et al.*, 2004), England (McGregor, 2005; Carder *et al.*, 2005; McGregor *et al.*, 2004; Kovats *et al.*, 2004;), Greece (Bartzokas *et al.*, 2004), Japan (Nakaji *et al.*, 2004), the United States (Cagle and Hubbard, 2005), and parts of Africa, Asia, Europe, Latin America and the Caribbean (Chang *et al.*, 2004), clearly demonstrate that global warming is actually *beneficial* to humanity, in that it reduces the incidence of cardiovascular disease related to low temperatures and wintry weather by a much greater degree than it increases the incidence of cardiovascular disease associated with high temperatures and summer heat waves.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/h/healtheffectscardio.php>.

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### 9.1.2. Respiratory Diseases

As with cardiovascular-related mortality, respiratory-related deaths are also more likely to be associated with cold conditions in cold countries. For example, in the Oslo study where Nafstad *et al.* (2001) found winter deaths due to cardiovascular problems to be 15% more numerous than similar summer deaths, they determined that *deaths due to respiratory diseases were fully 47% more numerous in winter than in summer*. Likewise, the London study of Hajat and Haines (2002) revealed that the number of doctor visits by the elderly was also higher in cool-season than warm-season months for all respiratory diseases. At mean temperatures below 5°C, in fact, the relationship between respiratory disease consultations and temperature was linear, and stronger at a time lag of 6 to 15 days, such that *a 1°C decrease in mean temperature below 5°C was associated with a 10.5% increase in all respiratory disease consultations*. In addition, Gouveia *et al.* (2003) found that death rates in Sao Paulo, Brazil, due to a 1°C cooling were *twice as great* as death rates due to a 1°C warming in adults, and *2.8 times greater* in the elderly.

In another study, Donaldson (2006) studied the effect of annual mean daily air temperature on the length of the yearly RSV season in England and Wales for 1981-2004. Results indicated that "the seasons associated with laboratory isolation of respiratory syncytial virus (for 1981-2004) and RSV-related emergency department admissions (for 1990-2004) ended 3.1 and 2.5 weeks earlier, respectively, per 1°C increase in annual central England temperature (P = 0.002 and 0.043, respectively)." Consequently, since "no relationship was observed between the start of each season and temperature," he reports that "the RSV season has become shorter." The implications of Donaldson's results are rather obvious. As he describes them, "these findings imply a health benefit of global warming in England and Wales associated with a reduction in the duration of the RSV season and its consequent impact on the health service."

Respiratory-related deaths were also investigated in the United States hot- and cold-city study of Braga *et al.* (2002), who found that increased temperature *variability* was the most relevant aspect of climate change with respect to this category of disease in this part of the world. Why is this finding important? Because Robeson (2002) has clearly demonstrated, from a 50-year study of daily temperatures at more than 1,000 U.S. weather stations, that temperature

variability *declines* with warming, and at a very substantial rate, so that *reduced temperature variability in a warmer world would lead to reductions in temperature-related deaths at both the high and low ends of the daily temperature spectrum at all times of the year.*

As is the case with human *cardiovascular* health, therefore, these several studies make it abundantly clear that a warming world should positively impact the *respiratory* health of the world's citizens.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/h/healtheffectsresp.php>.

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### 9.1.3. Vector-Borne Diseases

In a research report in *Science*, Rogers and Randolph (2000) note what is probably well known to all, namely, that "predictions of global climate change have stimulated forecasts that vector-borne diseases will spread into regions that are at present too cool for their persistence." Indeed, such predictions comprise one of the major global-warming scare-stories of the world's climate alarmists. There are, however, several problems with this scenario.

According to Reiter (2000), claims that malaria resurgence is the product of CO<sub>2</sub>-induced global warming ignore other important factors and disregard known facts. An historical analysis of malaria trends, for example, reveals that this disease was an important cause of illness and death in England during a period of *colder*-than-present temperatures throughout the Little Ice Age. What is more, its transmission began to decline only in the 19th century, during a

*warming* phase, when, according to Reiter, "temperatures were already much higher than in the Little Ice Age."

Given such events, why was malaria so prevalent in Europe during some of the coldest centuries of the past millennium .. and why we have only recently witnessed malaria's widespread decline at a time when temperatures have been warming? Clearly, there must be other factors at work that are more important than temperature. *And there are* -- factors such as the quality of public health services, irrigation and agricultural activities, land use practices, civil strife, natural disasters, ecological change, population change, use of insecticides, and the movement of people (Reiter, 2000; Reiter, 2001; Hay *et al.*, 2002).

Why, then, does the TSD and CSDs predict widespread future increases in malaria? They do it because nearly all of the analyses they cite have typically used only one, or at most two, climate variables to make predictions of the future distribution of the disease over the earth; and they generally do not include any of the non-climatic factors listed in the paragraph above. In one modeling study, for example, Rogers and Randolph (2000) employed a total of *five* climate variables and obtained very different results. Briefly, they used the present-day distribution of malaria to determine the specific climatic constraints that best define that distribution, after which the multivariate relationship they derived from this exercise was applied to future climate scenarios derived from state-of-the-art climate models, in order to map potential future geographical distributions of the disease.

The results of their study revealed very little change: a 0.84% increase in potential malaria exposure under the "medium-high" scenario of global warming and a 0.92% *decrease* under the "high" scenario. In consequence of these findings, Rogers and Randolph explicitly state that their quantitative model "contradicts prevailing forecasts of global malaria expansion," and that "it highlights the use [we would say *superiority*] of multivariate rather than univariate constraints in such applications."

Clearly, this study undercuts the climate-alarmist claim that any future warming of the globe will allow malaria to spread into current malaria-free regions, as do the studies of Hay *et al.* (2002) and Shanks *et al.* (2000). The first of these research groups investigated long-term trends in meteorological data at four East African highland sites that experienced significant increases in malaria cases over the past couple of decades, reporting that "temperature, rainfall, vapour pressure and the number of months suitable for *P. falciparum* transmission have not changed significantly during the past century or during the period of reported malaria resurgence." Hence, these factors could not be responsible for the observed increases in malaria cases. Likewise, Shanks *et al.* examined trends in temperature, precipitation and malaria rates in western Kenya over the period 1965-1997, finding absolutely no linkages among the variables.

Also working in Africa, Small *et al.* (2003) examined trends in a climate-driven model of malaria transmission between 1911 and 1995, using a spatially and temporally extensive gridded climate data-set to identify locations where the malaria transmission *climate suitability index*

had changed significantly over this time interval. Then, after determining areas of change, they more closely examined the underlying climate forcing of malaria transmission suitability for those localities. This protocol revealed that malaria transmission suitability did indeed increase because of climate change in specific locations of limited extent; but in Southern Mozambique, which was the only region for which climatic suitability consistently increased, the cause of the increase was increased *precipitation*, not temperature. In fact, Small *et al.* say that "climate warming, expressed as a systematic temperature increase over the 85-year period, does not appear to be responsible for an increase in malaria suitability over *any* [our italics] region in Africa." Hence, they concluded that "research on the links between climate change and the recent resurgence of malaria across Africa would be best served through refinements in maps and models of precipitation patterns and through closer examination of the role of nonclimatic influences," the great significance of which has recently been demonstrated by Reiter *et al.* (2003) for dengue fever, another important mosquito-borne disease.

Further examining the reemergence of malaria in the East African highlands were Zhou *et al.* (2004), who addressed the issue via a nonlinear mixed-regression model study that focused on the numbers of monthly malaria outpatients of the past 10-20 years in seven East African highland sites and their relationships to the numbers of malaria outpatients during the previous time period, seasonality and climate variability. In doing so, they say that "for all seven study sites, we found highly significant nonlinear, synergistic effects of the interaction between rainfall and temperature on malaria incidence, indicating that *the use of either temperature or rainfall alone is not sensitive enough for the detection of anomalies that are associated with malaria epidemics* [our italics]," as has also been found by Githeko and Ndegwa (2001), Shanks *et al.* (2002) and Hay *et al.* (2002). What is more, *climate variability* -- not just *temperature* or not just *warming* -- contributed less than 20% of the temporal variance in the number of malaria outpatients, and at only two out of the seven sites studied.

In light of their findings, Zhou *et al.* concluded that "malaria dynamics are largely driven by autoregression and/or seasonality in these sites," and that "the observed large among-site variation in the sensitivity to climate fluctuations may be governed by complex interactions between climate and biological and social factors," including "land use, topography, *P. falciparum* genotypes, malaria vector species composition, availability of vector control and healthcare programs, drug resistance, and other socioeconomic factors," among which are "failure to seek treatment or delayed treatment of malaria patients, and HIV infections in the human population," which they say have "become increasingly prevalent." Hence, it would appear that the so-called *unprecedented* global warming of the past century or so, which is claimed in the TSD and CSDs to have significantly accelerated over the past couple of decades, should be the *least* of our worries with respect to this subject... *or* that the claimed acceleration of warming is more imagined than real.

Prefacing another revealing study, Kuhn *et al.* (2003) say "there has been much recent speculation that global warming may allow the reestablishment of malaria transmission in previously endemic areas such as Europe and the United States." In particular, they note that "the British Chief Medical Officer's recent report [*Getting Ahead of the Curve: A Strategy for*

*Combating Infectious Diseases (Including Other Aspects of Health Protection)*, Department of Health (2002), London] asserted that 'by 2050 the climate of the UK may be such that indigenous malaria could become re-established', which is the same mantra that is incessantly chanted by the world's climate alarmists. Consequently, to investigate the robustness of this hypothesis, they analyzed the determinants of temporal trends in malaria deaths within England and Wales from 1840-1910.

With respect to temperature changes over the period of study, this analysis indicated that "a 1°C increase or decrease was responsible for an increase in malaria deaths of 8.3% or a decrease of 6.5%, respectively," which explains "the malaria epidemics in the 'unusually hot summers' of 1848 and 1859." Nevertheless, the long-term near-linear temporal decline in malaria deaths over the period of study, in the words of the researchers, "was probably driven by nonclimatic factors," among which they list increasing livestock populations (which tend to divert mosquito biting from humans), decreasing acreages of marsh wetlands (where mosquitoes breed), as well as "improved housing, better access to health care and medication, and improved nutrition, sanitation, and hygiene." They additionally note that the number of secondary cases arising from each primary imported case "is currently minuscule," as demonstrated by the absence of any secondary malaria cases in the UK since 1953.

Although simplistic model simulations may suggest that the increase in temperature predicted for Britain by 2050 is likely to cause an 8-14% increase in the *potential* for malaria transmission, Kuhn *et al.* say "the projected increase in proportional risk is clearly insufficient to lead to the reestablishment of endemicity." Expanding on this statement, they note that "the national health system ensures that imported malaria infections are detected and effectively treated and that gametocytes are cleared from the blood in less than a week." For Britain, therefore, they conclude that "a 15% rise in risk might have been important in the 19th century, but such a rise is now highly unlikely to lead to the reestablishment of indigenous malaria," since "socioeconomic and agricultural changes" have greatly altered the cause-and-effect relationships of the past.

In the introduction to his review about what was known to this point in time about the putative link between global warming and the spread of infectious diseases, Zell (2004) stated that many people "assume a correlation between increasing disease incidence and global warming." However, as he concluded after studying the issue in considerable depth, "the factors responsible for the emergence/reemergence of vector-borne diseases are complex and mutually influence each other," citing as an example of this complexity the fact that "the incidence and spread of parasites and arboviruses are affected by insecticide and drug resistance, deforestation, irrigation systems and dams, changes in public health policy (decreased resources of surveillance, prevention and vector control), demographic changes (population growth, migration, urbanization), and societal changes (inadequate housing conditions, water deterioration, sewage, waste management)." Therefore, as he continues, "it may be over-simplistic to attribute emergent/re-emergent diseases to climate change and sketch the menace of devastating epidemics in a warmer world," such as Al Gore does in *An Inconvenient Truth*. Indeed, Zell states that "variations in public health practices and lifestyle



can *easily* [our italics] outweigh changes in disease biology," especially those that might be caused by global warming.

In a rather different type of study, but one that is extremely pertinent, Tuchman *et al.* (2003) (1) took leaf litter from *Populus tremuloides* (Michaux) trees that had been grown out-of-doors in open-bottom root boxes located within open-top aboveground chambers maintained at atmospheric CO<sub>2</sub> concentrations of either 360 or 720 ppm for an entire growing season, (2) incubated the leaf litter for 14 days in a nearby stream, and (3) fed the incubated litter to four species of detritivorous mosquito larvae to assess its effect on their development rates and survivorship. This work revealed that larval mortality was 2.2 times higher for *Aedes albopictus* (Skuse) mosquitos that were fed leaf litter that had been produced in the high-CO<sub>2</sub> chambers than it was for those fed litter that had been produced in the ambient-air chambers. In addition, they found that larval development rates of *Aedes triseriatus* (Say), *Aedes aegypti* (L.) and *Armigeres subalbatus* (Coquillett) were slowed by 78%, 25% and 27%, respectively, when fed litter produced in the high-CO<sub>2</sub> as opposed to the ambient-CO<sub>2</sub> chambers, so that mosquitoes of these species spent 20, 11 and 9 days longer in their respective larval stages when feeding on litter produced in the CO<sub>2</sub>-enriched as compared to the ambient-CO<sub>2</sub> chambers. As for the reason behind these observations, the researchers suggest that "increases in lignin coupled with decreases in leaf nitrogen induced by elevated CO<sub>2</sub> and subsequent lower bacterial productivity [on the leaf litter in the water] were probably responsible for [the] decreases in survivorship and/or development rate of the four species of mosquitoes."

What is the significance of these findings?

In the words of Tuchman *et al.*, "the indirect impacts of an elevated CO<sub>2</sub> atmosphere on mosquito larval survivorship and development time could potentially be great," because longer larval development times could result in fewer cohorts of mosquitoes surviving to adulthood; and with fewer mosquitoes around, there should be lower levels of mosquito-borne diseases, for which blessing we would have the ongoing rise in the atmosphere's CO<sub>2</sub> concentration to thank.

In another major review of the potential impacts of global warming on vector-borne diseases, Rogers and Randolph (2006) focus on recent upsurges of malaria in Africa, asking the question "Has climate change already had an impact?" They go on to demonstrate that "evidence for increasing malaria in many parts of Africa is overwhelming, but the more likely causes for most of these changes to date include land-cover and land-use changes and, most importantly, drug resistance rather than any effect of climate," noting that "the recrudescence of malaria in the tea estates near Kericho, Kenya, in East Africa, *where temperature has not changed significantly* [our italics], shows all the signs of a disease that has escaped drug control following the evolution of chloroquine resistance by the malarial parasite." They then go on to explain that "malaria waxes and wanes to the beat of two rhythms: an annual one dominated by local, seasonal weather conditions and a *ca.* 3-yearly one dominated by herd immunity," noting that "effective drugs suppress both cycles before they can be expressed," but that "this produces a population which is mainly or entirely dependent on drug effectiveness, and which suffers the

consequence of eventual drug failure, during which the rhythms reestablish themselves, as they appear to have done in Kericho."

Last of all, Childs *et al.* (2006) present a detailed analysis of malaria incidence in northern Thailand based on a quarter-century monthly time series (January 1977 through January 2002) of total malaria cases in the country's 13 northern provinces. Over this time period, when climate alarmists claim the world warmed at a rate and to a level that were *unprecedented over the prior two millennia*, they report there was an approximately constant rate of *decline* in total malaria incidence (from a mean monthly incidence in 1977 of 41.5 cases per hundred thousand people to 6.72 cases per hundred thousand people in 2001), due primarily to a reduction in cases positive for *Plasmodium falciparum* (mean monthly incidence in 1977 and 2001 of 28.6 and 3.22 cases per 100,000 people, respectively) and secondarily to a reduction in cases positive for *P. vivax* (mean monthly incidence in 1977 and 2001 of 12.8 and 3.5 cases per 100,000 people, respectively). Consequently, noting that "there has been a steady reduction through time of total malaria incidence in northern Thailand, with an average decline of 6.45% per year," they say this result "reflects changing agronomic practices and patterns of immigration, as well as the success of interventions such as vector control programs, improved availability of treatment and changing drug policies."

In light of the many findings described above, the claim that malaria will expand across the globe and intensify *as a result of CO<sub>2</sub>-induced warming* is seen to be basically bogus. In the words of Dye and Reiter (2000), "given adequate funding, technology, and, above all, commitment, the campaign to 'Roll Back Malaria,' spearheaded by the World Health Organization, will have halved deaths related to [malaria] by 2010," independent of whatever tack earth's climate might take in the interim.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/m/malaria.php>, <http://www.co2science.org/subject/h/healtheffectsdenque.php>, and <http://www.co2science.org/subject/h/healtheffectsyellfev.php>.

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#### 9.1.4. Tick-Borne Diseases

Similar to vector-borne diseases, climate alarmists also conclude that one of the likely consequences of the increase in temperature predicted to be produced by anthropogenic CO<sub>2</sub> emissions would be expanded geographic ranges of *tick-borne diseases*. We here consider the reliability of this claim as illuminated by some studies of the subject we have reviewed on our website (<http://www.co2science.org/subject/h/summaries/healtheffectstick.php>).

We begin with the study of Randolph and Rogers (2000), who report that tick-borne encephalitis (TBE) "is the most significant vector-borne disease in Europe and Eurasia," having "a case morbidity rate of 10-30% and a case mortality rate of typically 1-2% but as high as 24% in the Far East." The disease is caused by a flavivirus (TBEV), which is maintained in natural rodent-tick cycles; and humans may be infected with it if bitten by an infected tick or by drinking untreated milk from infected sheep or goats.

Early writings on the relationship of TBE to global warming predicted it would expand its range and become more of a threat to humans in a warmer world. However, Randolph and Rogers indicate that "like many vector-borne pathogen cycles that depend on the interaction of so many biotic agents with each other and with their abiotic environment, enzootic cycles of TBEV have an inherent fragility," so that "their continuing survival or expansion cannot be predicted from simple univariate correlations," as is commonly done by climate alarmists intent on scaring people into reducing CO<sub>2</sub> emissions on the basis of false premises. Hence, the two researchers decided to explore the subject in greater detail than had ever been done before. Confining their analysis to Europe, Randolph and Rogers first matched the present-day distribution of TBEV to the present-day distributions of five climatic variables: monthly mean, maximum and minimum temperatures, plus rainfall and saturation vapor pressure, "to provide a multivariate description of present-day areas of disease risk." Then, they applied this understanding to outputs of a general circulation model of the atmosphere that predicted how these five climatic variables may change in the future.

The results of these operations indicated that the distribution of TBEV might expand both north and west of Stockholm, Sweden, in a warming world. For most other parts of Europe, however, the two researchers say that "fears for increased extent of risk from TBEV caused by global climate change appear to be unfounded." In fact, they found that "the precise conditions required for enzootic cycles of TBEV are predicted to be disrupted" in response to global warming, and that the new climatic state "appears to be lethal for TBEV." This finding, in their words, "gives the lie to the common perception that a warmer world will necessarily be a world under greater threat from vector-borne diseases." In the case of TBEV, in fact, they report that the predicted change "appears to be to our advantage."

Also reporting that "it is often suggested that one of the most important societal consequences of climate change may be an increase in the geographic distribution and transmission intensity of vector-borne disease," Estrada-Peña (2003) evaluated the effects of various abiotic factors on the habitat suitability of four tick species that are major vectors of livestock pathogens in

South Africa. This work revealed that "year-to-year variations in the forecasted habitat suitability over the period 1983-2000 show a clear decrease in habitat availability, which is attributed primarily to increasing temperature in the region over this period." In addition, when climate variables were projected to the year 2015, Estrada-Peña found that "the simulations show a trend toward the destruction of the habitats of the four tick species," which is just the *opposite* of what is predicted by the TSD and CRDs.

Another scientist who has noted that many people "assume a correlation between increasing disease incidence and global warming" is Zell (2004), who reviewed the scientific literature pertaining to the subject and determined that "the factors responsible for the emergence/reemergence of vector-borne diseases are complex and mutually influence each other," citing as an example of this complexity the fact that "the incidence and spread of parasites and arboviruses are affected by insecticide and drug resistance, deforestation, irrigation systems and dams, changes in public health policy (decreased resources of surveillance, prevention and vector control), demographic changes (population growth, migration, urbanization), and societal changes (inadequate housing conditions, water deterioration, sewage, waste management)."

In light of these many complicating factors, Zell says "it may be over-simplistic to attribute emergent/re-emergent diseases to climate change and sketch the menace of devastating epidemics in a warmer world." Indeed, he concludes that "variations in public health practices and lifestyle can easily outweigh changes in disease biology," especially those that might be caused by global warming. What is more, these public health and lifestyle changes could be implemented *now*, if we chose to do so, and at only a tiny *fraction* of the cost that would be needed to make even the *smallest* of changes in the future course of earth's air temperature. If we are truly worried about the status of vector-borne diseases in a warmer world, this is the tack we should take.

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### 9.1.5. All Diseases

In a study of mortality in general, Keatinge and Donaldson (2001) analyzed the effects of temperature, wind, rain, humidity and sunshine during high pollution days in the greater London area over the period 1976-1995 to determine what weather and/or pollution factors

have the biggest influence on human mortality. Their most prominent finding was that simple plots of mortality rate versus daily air temperature revealed a linear increase in deaths as temperatures fell from 15°C to near 0°C. Mortality rates at temperatures above 15°C were, in the words of the researchers, "grossly alinear," showing no trend. Days with high pollutant concentrations were colder than average, but a multiple regression analysis revealed that no pollutant was associated with a significant increase in mortality among people over fifty years of age. Indeed, *only low temperatures were shown to have a significant effect on both immediate (1 day after the temperature perturbation) and long-term (up to 24 days after the temperature perturbation) mortality rates.*

In a closely allied study, Keatinge *et al.* (2000) examined heat- and cold-related mortality in north Finland, south Finland, southwest Germany, the Netherlands, Greater London, north Italy, and Athens, Greece, in people aged 65-74. For each of these regions, they determined the 3°C temperature interval of lowest mortality and then evaluated mortality deviations from that base level as temperatures rose and fell by 0.1°C increments. The result, according to the researchers, was that "all regions showed more annual cold related mortality than heat related mortality." In fact, over the seven regions studied, *annual cold related deaths were nearly ten times greater than annual heat related deaths.* The scientists also note that the very successful adjustment of the different populations they studied to widely different summer temperatures "gives grounds for confidence that they would adjust successfully, with little increase in heat related mortality, to the global warming of around 2°C predicted to occur in the next half century." Indeed, they say their data suggest that "any increases in mortality due to increased temperatures would be outweighed by much larger short term declines in cold related mortalities." For the population of Europe, therefore, an increase in temperature would appear to be a climate change for the better.

Gouveia *et al.* (2003) conducted a similar study in Sao Paulo, Brazil, where they tabulated the numbers of daily deaths from all causes (excepting violent deaths and deaths of infants up to one month of age), which they obtained from the city's mortality information system for the period 1991-1994. They then analyzed these data for *children* (less than 15 years of age), *adults* (ages 15-64), and the *elderly* (age 65 and above) with respect to the impacts of warming and cooling. For each 1°C increase above the minimum-death temperature of 20°C for a given and prior day's mean temperature, there was a 2.6% increase in deaths from all causes in children, a 1.5% increase in deaths from all causes in adults, and a 2.5% increase in deaths from all causes in the elderly. For each 1°C decrease *below* the 20°C minimum-death temperature, however, *the cold effect was greater*, with increases in deaths from all causes in children, adults and the elderly registering 4.0%, 2.6% and 5.5%, respectively, which cooling-induced death rates are 54%, 73% and 120% *greater* than those attributable to warming.

In a similar study conducted in Shanghai, China, from 1 Jun 2000 to 31 Dec 2001, Kan *et al.* (2003) found a V-like relationship between total mortality and temperature that had a minimum mortality risk at 26.7°C. Above this temperature, they note that "total mortality increased by 0.73% for each degree Celsius increase; while for temperatures below the optimum value, total mortality decreased by 1.21% for each degree Celsius increase." Hence, it

can be appreciated that the net effect of a warming of the climate of Shanghai would likely be *reduced* mortality on the order of 0.5% per degree Celsius increase in temperature, *or perhaps even more*, in light of the fact that the warming of the past few decades has been primarily due to increases in daily *minimum* temperatures.

In the United States, Goklany and Straja (2000) studied deaths due to all causes over the period 1979-97, finding there were no trends due to either extreme heat or cold in the entire population or, even more remarkably, in the older more susceptible age groups, i.e., those aged 65 and over, 75 and over, and 85 and over. Nevertheless, *deaths due to extreme cold exceeded those due to extreme heat by 80% to 125%*. With respect to the absence of *trends* in U.S. death rates attributable to either extreme heat or cold, Goklany and Straja say this observation "suggests that adaptation and technological change may be just as important determinants of such trends as more obvious meteorological and demographic factors."

Donaldson *et al.* (2003) suggest much the same thing. For three areas of the world -- North Carolina, USA; South Finland; and Southeast England -- they determined the mean daily May-August 3°C temperature bands in which deaths of people aged 55 and above were at a minimum. Then they compared heat- and cold-related deaths that occurred at temperatures above and below this optimum temperature interval for each region, after which they determined how heat-related deaths in the three areas changed between 1971 and 1997 in response to: (1) the 1.0°C temperature rise that was experienced in North Carolina over this period (from an initial temperature of 23.5°C), (2) the 2.1°C temperature rise experienced in Southeast England (from an initial temperature of 14.9°C), and (3) the unchanging 13.5°C temperature of South Finland.

First, it was determined that the 3°C temperature band at which mortality was at its local minimum was lowest for the coolest region (South Finland), highest for the warmest region (North Carolina), and intermediate for the region of intermediate temperature (Southeast England). This finding suggests that the populations of the three regions were somewhat acclimated to their respective thermal regimes. Second, for *each* of the three regions, it was determined that *cold*-related mortality (expressed as excess mortality at temperatures *below* the region's optimum 3°C temperature band), was greater than *heat*-related mortality (expressed as excess mortality at temperatures *above* the region's optimum 3°C temperature band).

As for the third aspect of the study, i.e., changes in heat-related mortality from 1971 to 1997, it was determined that in the coldest of the three regions (South Finland, where there was *no change* in temperature over the study period), heat-related deaths per million inhabitants in the 55-and-above age group *declined* from 382 to 99. In somewhat warmer Southeast England, however, where it warmed by a whopping 2.1°C over the study period, heat-related deaths per million of the at-risk age cohort *still declined*, but this time from only 111 to 108. Last of all, in the warmest of the three regions (North Carolina, USA, where mean daily May-August temperature rose by 1.0°C over the study period), corresponding heat-related deaths *also fell*, and this time from 228 to a mere 16 per million.

From these several observations we learn that most people can adapt to both warmer and cooler climates and that cooling tends to produce many more deaths than warming, irrespective of the initial temperature regime. As for the reason behind the third observation -- the dramatic decline in heat-related deaths in response to warming in the hottest region of the study (North Carolina) -- Donaldson *et al.* (2003) attribute it to the increase in the availability of air conditioning in the South Atlantic region of the United States, where they note that the percentage of households with some form of air conditioning rose from 57% in 1978 to 72% in 1997. With respect to the declining heat-related deaths in the other two areas, they say "the explanation is likely to lie in the fact that both regions shared with North Carolina an increase in prosperity, which could be expected to increase opportunities for avoiding heat stress."

Another revealing investigation into the comparative dangers of unseasonably hot and cold temperatures was conducted by Huynen *et al.* (2001), who analyzed mortality rates in the entire population of Holland. For the 19-year period 1 January 1979 through 31 December 1997, the group of five scientists compared the numbers of deaths in people of all ages that occurred during well-defined heat waves and cold spells. Their bottom-line findings indicated there was a total excess mortality of 39.8 deaths *per day* during heat waves and 46.6 deaths *per day* during cold spells.

These numbers indicate that a typical cold-spell *day* kills at a rate that is 17% greater than a typical heat-wave *day* in the Netherlands. In addition, the researchers note that the heat waves they studied ranged from 6 to 13 days in length, while the cold spells lasted 9 to 17 days, making the average cold spell approximately 37% longer than the average heat wave. Adjusting for this duration differential thus makes the number of deaths *per cold spell* in the Netherlands fully 60% greater than the number of deaths *per heat wave*. What is more, excess mortality *continued* during the whole month *after* the cold spells, leading to even *more* deaths; while in the case of heat waves, there actually appeared to be mortality *deficits* in the following month, which suggests, in the words of the authors, "that some of the heat-induced increase in mortality can be attributed to those whose health was already compromised" or "who would have died in the short term anyway." This same conclusion has also been reached in a number of other studies (Kunst *et al.*, 1993; Alberdi *et al.*, 1998; Eng and Mercer, 1998; Rooney *et al.*, 1998). It is highly likely, therefore, that the 60% greater death toll we have calculated for Dutch cold spells as compared to Dutch heat waves is a vast *underestimate* of the true differential killing power of these two extreme weather phenomena.

The Dutch could well ask themselves, therefore, "Will global climate change reduce thermal stress in the Netherlands?" ... which is exactly what the senior and second authors of the Huynen *et al.* paper did in a letter to the editor of *Epidemiology* that bore that very title (Martens and Huynen, 2001). Based on the predictions of nine different GCMs for an atmospheric CO<sub>2</sub> concentration of 550 ppm in the year 2050 -- which implied a 50% increase in Dutch heat waves and a 67% drop in Dutch cold spells -- they calculated a total mortality *decrease* for Holland of approximately 1100 people *per year* at that point in time.



Yes, global warming -- if it continues, and for whatever reason -- will result, not in more lives *lost*, but in more lives *saved*. And it's not just the Dutch that will be thus blessed; data from all over the world tell the same story.

Take Germany, for instance. Laschewski and Jendritzky (2002) analyzed daily mortality rates of the population of Baden-Wurttemberg (10.5 million inhabitants) over the 30-year period 1958-1997 to determine the sensitivity of the people living in this moderate climatic zone of southwest Germany to long-and short-term episodes of heat and cold. With respect to long-term conditions, they note that the mortality data "show a marked seasonal pattern with a minimum in summer and a maximum in winter." With respect to short-term conditions, they report that "cold spells lead to excess mortality to a relatively small degree, which lasts for weeks," and that "the mortality increase during heat waves is more pronounced, but is followed by lower than average values in subsequent weeks." These scientists also say this latter observation suggests that people who died from short-term exposure to heat likely "would have died in the short term anyway."

With respect to this short-term mortality displacement in the case of heat-related deaths, we note that the authors' data demonstrate it is precisely that, i.e., merely a *displacement* of deaths and not an overall increase. They found, for example, that the mean duration of above-normal mortality for the 51 heat episodes that occurred from 1968 to 1997 was 10 days, with a mean increase in mortality of 3.9%, after which there was a mean *decrease* in mortality of 2.3% for 19 days. Hence, the *net* effect of the two perturbations was essentially nil (actually, a calculated overall *decrease* in mortality of 0.2% over the full 29-day period).

In light of the knowledge gained from these several studies of the effects of temperature on human mortality due to *all* health problems, it can readily be appreciated that it is *cooling* that kills, not warming. Hence, those who claim to be concerned about the health effects of climate change are being dishonest when they say that CO<sub>2</sub>-induced global warming is killing people. In point of fact, CO<sub>2</sub>-induced global warming -- if it is even occurring at all -- is enabling earth's populace to actually lead both *longer* and *more productive* lives.

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## **9.2. Non-Climatic Health Effects of Elevated CO<sub>2</sub>**

Even if atmospheric CO<sub>2</sub> enrichment caused significant global warming (which is highly unlikely), and even if global warming caused an increase in human death rate (which it clearly does not), it would still be necessary for the EPA to consider *other* potential health effects of atmospheric CO<sub>2</sub> enrichment that are *not* related to climate in order to determine the *net* effect of elevated levels of atmospheric CO<sub>2</sub> on human health and longevity. Hence, we next explore several aspects of this subject about which little or nothing at all is said -- *positive* effects of atmospheric CO<sub>2</sub> enrichment that tend to *enhance* people's quality of life.

### 9.2.1. Direct Health Effects of Elevated CO<sub>2</sub>

Almost all trace elements and compounds, even beneficial ones, can be poisonous if ingested or inhaled in large enough concentrations. So what about carbon dioxide? Do we have to worry about any deleterious health effects as its atmospheric concentration continues to climb?

As correctly pointed out in the EPA's Technical Support Document, inhaling *very* high concentrations of atmospheric CO<sub>2</sub> can induce a state of *hypercapnia* in people (Nahas *et al.*, 1968; Brackett *et al.*, 1969; van Ypersele de Strihou, 1974). Characterized by an excessive amount of CO<sub>2</sub> in the blood, which typically results in *acidosis*, this condition is accompanied by headache, nausea, visual disturbances, and is sometimes fatal (Poyart and Nahas, 1968; Turino *et al.*, 1974). Several studies have demonstrated, however, that these problems do not seriously impact human health until the air's CO<sub>2</sub> concentration reaches approximately 15,000 ppm (Luft *et al.*, 1974; Schaefer, 1982), which is approximately 40 times greater than its current concentration.

Clearly, therefore, we do not have to worry about there being any direct adverse health effects associated with the ongoing rise in the air's CO<sub>2</sub> content, even if it were to increase by a factor of ten, which is probably all that could be achieved by burning the entire supply of fossil fuels in the crust of the earth. In fact, the *current* CO<sub>2</sub> concentration of the air in many homes and buildings is often two to three times greater than the CO<sub>2</sub> concentration of outdoor air (Idso, 1997), which in large cities is itself often elevated by several tens of percent above the CO<sub>2</sub> concentration of rural air (Idso *et al.* 1998, 2002).

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### 9.2.2. Indirect Health Effects of Elevated CO<sub>2</sub>

The effects of atmospheric CO<sub>2</sub> enrichment on *food production* must also be considered in any assessment of the health effects of the historical and still-ongoing rise in the air's CO<sub>2</sub> content. Here, we begin our investigation of this subject with a brief review of the well-known *aerial fertilization effect* of atmospheric CO<sub>2</sub> enrichment and how it impacts the human health issue.

#### 9.2.2.1. Food Production

First and foremost, people must have *sufficient* food, simply to sustain themselves; and the rise in the atmosphere's CO<sub>2</sub> concentration that has occurred since the inception of the Industrial Revolution (an increase of approximately 100 ppm) has done wonders for humanity in this regard.

##### 9.2.2.1.1. THE PAST

In a revealing study of the beneficial impact of mankind's *historical* CO<sub>2</sub> emissions on world food production, Mayeux *et al.* (1997) grew two cultivars of commercial wheat in a 38-meter-long soil container topped with a transparent tunnel-like polyethylene cover within which a CO<sub>2</sub> gradient was created that varied from approximately 350 ppm at one end of the tunnel to about 200 ppm at the other end. Both of the wheat cultivars were irrigated weekly over the first half of the 100-day growing season, so as to maintain soil water contents near optimum conditions. Over the last half of the season, however, this regimen was maintained on only half of the wheat of each cultivar, in order to create both water-stressed and well-watered treatments.

At the conclusion of the experiment, the scientists determined that the growth response of the wheat was a linear function of atmospheric CO<sub>2</sub> concentration in both cultivars under both adequate and less-than-adequate soil water regimes. Based on the linear regression equations they developed for grain yield in these situations, we calculate that the 100-ppm increase in atmospheric CO<sub>2</sub> concentration experienced over the past century and a half should have increased the mean grain yield of the two wheat cultivars by about 72% under well-watered conditions and 48% under water-stressed conditions, for a mean yield increase on the order of 60% under the full range of moisture conditions likely to have existed throughout the entire real world.

It is also important to note that this CO<sub>2</sub>-induced yield enhancement was not restricted to wheat. Based on the voluminous amount of data summarized by Idso and Idso (2000) for the world's major food crops, the calculations we have made for wheat can be scaled to determine what the past 150-year increase in atmospheric CO<sub>2</sub> concentration likely did for the productivity of other agricultural staples. Doing so, we find that the Industrial Revolution's flooding of the air with CO<sub>2</sub> resulted in mean yield increases on the order of 70% for other C<sub>3</sub> cereals, 28% for C<sub>4</sub> cereals, 33% for fruits and melons, 62% for legumes, 67% for root and tuber crops, and 51% for vegetables.

#### 9.2.2.1.2. THE FUTURE

Clearly, the historical increase in the air's CO<sub>2</sub> content that has been experienced to date has vastly benefited mankind and enabled our numbers to grow considerably. In fact, the very existence of many of the people who read these words may well be attributed to that phenomenon. But what of the future? The population explosion of our species has not yet subsided; and there is real concern about our ability to feed the projected population of the world a mere fifty years hence.

Tilman *et al.* (2001) address this problem in an analysis of the global environmental impacts of agricultural expansion that may occur over the next half-century. Based on projected increases in population, *and even accounting for expected concomitant advances in technological expertise*, they conclude that the task of meeting the global food demand expected to exist in the year 2050 will likely exact a heavy environmental toll and produce great societal impacts.

What are the specific problems? Tilman and his colleagues report that "humans currently appropriate more than a third of the production of terrestrial ecosystems and about half of usable freshwaters," noting that this usurpation of natural resources will increase even more in the future. In terms of the amount of land devoted to agriculture, they calculate an 18% increase over the present by the year 2050; but because developed countries are expected to *withdraw* large areas of land from farming over the next fifty years, the net loss of natural ecosystems to cropland and pasture in *developing* countries will amount to about half of all potentially suitable remaining land, which would "represent the worldwide loss of natural ecosystems larger than the United States."

The scientists go on to say that this phenomenon "could lead to the loss of about a third of remaining tropical and temperate forests, savannas, and grasslands." What is more, in a worrisome reflection upon the consequences of these land-use changes for both plants and animals, they remind us that species extinction follows rapidly on the heels of habitat destruction. Finally, in another acknowledgement of just how serious the situation is, Tilman and his associates report that "even the best available technologies, fully deployed, cannot prevent many of the forecasted problems."

So what can possibly be done to avert this future food production shortfall and its devastating consequences that "even the best available technologies, fully deployed," cannot prevent? This is the question that was addressed by Idso and Idso (2000) in their treatise entitled *Forecasting World Food Supplies: The Impact of the Rising Atmospheric CO<sub>2</sub> Concentration*; and it was their conclusion that -- *after all that man can do* -- the aerial fertilization effect of the increase in the air's CO<sub>2</sub> content that is expected to occur by the year 2050 would be *just barely sufficient*, in the mean, to assure the agricultural productivity required to prevent mass starvation in many parts of the globe without usurping what little of the natural world would remain at that time.

In view of these observations, not only is the ongoing rise in the air's CO<sub>2</sub> content essential for the future well-being of man, *it is essential to the future well-being of the entire biosphere.*

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/a/agriculture.php>.

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### 9.2.2.2. Quality of Food

Clearly, *quantity* of food is mankind's number one concern when it comes to survival; but after survival is assured, *quality* of food rises to the fore. What role does the ongoing rise in the air's CO<sub>2</sub> content play here?

#### 9.2.2.2.1. PROTEIN CONTENT

In a review of the scientific literature related to effects of atmospheric CO<sub>2</sub> enrichment on plant constituents of significance to human health, Idso and Idso (2001) cited a number of studies where elevated levels of atmospheric CO<sub>2</sub> either increased, decreased or had no effect on the protein concentrations of various agricultural crops, the first two of which consequences have

subsequently also been observed by Kaddour and Fuller (2004) and Veisz *et al.* (2005), respectively, in wheat.

In the case of this particular crop - which according to Wittwer (1995) is "the most widely grown plant in the world today," contributing "more calories and protein to the human diet than any other food" - Pleijel *et al.* (1999) were able to bring some semblance of order to this confusing situation by analyzing the results of 16 open-top chamber experiments that had been conducted on spring wheat in Denmark, Finland, Sweden and Switzerland between 1986 and 1996. In addition to CO<sub>2</sub> enrichment of the air, these experiments included increases and decreases in atmospheric ozone (O<sub>3</sub>); and Pleijel *et al.* found that when increasing O<sub>3</sub> pollution reduced wheat grain yield, it simultaneously increased the protein concentration of the grain. They also found that when O<sub>3</sub> was scrubbed from the air and grain yield was thereby increased, the protein concentration of the grain was decreased. Moreover, this same relationship described the degree to which grain protein concentration dropped when atmospheric CO<sub>2</sub> enrichment increased grain yield. Hence, it became clear that whenever the grain yield of the wheat was changed -- by CO<sub>2</sub>, O<sub>3</sub> or even water stress, which was also a variable in one of the experiments -- grain protein concentrations either moved up or down along a common linear relationship in the opposite direction to the change in grain yield elicited by the CO<sub>2</sub>, O<sub>3</sub> or water stress treatment.

In an earlier study of CO<sub>2</sub> and O<sub>3</sub> effects on wheat grain yield and quality, Rudorff *et al.* (1996) obtained essentially the same result. They observed, for example, that "flour protein contents were increased by enhanced O<sub>3</sub> exposure and reduced by elevated CO<sub>2</sub>" but that "the combined effect of these gases was minor." Hence, they concluded that "the concomitant increase of CO<sub>2</sub> and O<sub>3</sub> in the troposphere will have no significant impact on wheat grain quality."

Earlier still, Evans (1993) had found similar relationships to exist for several other crops, further observing them to be greatly affected by soil nitrogen availability. It is highly likely, therefore, that the differing availability of soil nitrogen could have been responsible for some of the differing results observed in the many other studies reviewed by Idso and Idso (2001); and, in fact, that is precisely what the study of Rogers *et al.* (1996) suggests. Although the latter investigators observed CO<sub>2</sub>-induced reductions in the protein concentration of flour derived from wheat plants growing at low soil nitrogen concentrations, no such reductions were evident when the soil nitrogen supply was increased to a higher rate of application. Hence, Pleijel *et al.* concluded that the oft-observed negative impact of atmospheric CO<sub>2</sub> enrichment on grain protein concentration would probably be alleviated by higher applications of nitrogen fertilizers; and the study of Kimball *et al.* (2001) confirmed their hypothesis.

Kimball *et al.* studied the effects of a 50% increase in atmospheric CO<sub>2</sub> concentration on wheat grain nitrogen concentration and the baking properties of the flour derived from that grain throughout four years of free-air CO<sub>2</sub> enrichment experiments. In the first two years of their study, soil water content was an additional variable; and in the last two years, soil nitrogen content was a variable. The most influential factor in reducing grain nitrogen concentration

was determined to be low soil nitrogen; and under this condition, atmospheric CO<sub>2</sub> enrichment further reduced grain nitrogen and protein concentrations, although the change was much less than that caused by low soil nitrogen. When soil nitrogen was *not* limiting, however, increases in the air's CO<sub>2</sub> concentration did *not* affect grain nitrogen and protein concentrations; neither did they reduce the baking properties of the flour derived from the grain. Hence, it would appear that given sufficient water and nitrogen, atmospheric CO<sub>2</sub> enrichment can significantly increase wheat grain yield without sacrificing grain protein concentration in the process.

There are some situations, however, where atmospheric CO<sub>2</sub> enrichment has actually been found to *increase* the protein concentration of wheat. Agrawal and Deepak (2003), for example, grew two cultivars of wheat (*Triticum aestivum* L. cv. Malviya 234 and HP1209) in open-top chambers maintained at atmospheric CO<sub>2</sub> concentrations of 350 and 600 ppm alone and in combination with 60 ppb SO<sub>2</sub> to study the interactive effects of elevated CO<sub>2</sub> and this major air pollutant on crop growth. They found that exposure to the elevated SO<sub>2</sub> caused a 13% decrease in foliar protein concentrations in both cultivars; but when the plants were concomitantly exposed to an atmospheric CO<sub>2</sub> concentration of 600 ppm, leaf protein levels only decreased by 3% in HP1209, while they actually *increased* by 4% in Malviya 234.

In the case of rice - which according to Wittwer (1995) is "the basic food for more than half the world's population," supplying "more dietary energy than any other single food" - Jablonski *et al.* (2002) conducted a wide-ranging review of the scientific literature, finding that it too appeared to suffer no reduction in grain nitrogen (protein) concentration in response to atmospheric CO<sub>2</sub> enrichment. Likewise, they found no CO<sub>2</sub>-induced decrease in seed nitrogen concentration in the studies of *legumes* they reviewed. This finding is also encouraging, since according to Wittwer (1995) legumes "are a direct food resource providing 20% of the world's protein for human consumption," as well as "about two thirds of the world's protein concentrate for livestock feeding." What is more, the *biomass* of the CO<sub>2</sub>-enriched wheat, rice and legumes was found by Jablonski *et al.* to be significantly increased above that of the same crops grown in normal air. Hence, there will likely be a vast increase in the total amount of protein that can be made available to humanity in a future CO<sub>2</sub>-enriched world, both directly via food crops and indirectly via livestock.

With respect to the leguminous soybean, Thomas *et al.* (2003) additionally note that "oil and protein comprise ~20 and 40%, respectively, of the dry weight of soybean seed," which "unique chemical composition," in their words, "has made it one of the most valuable agronomic crops worldwide." In addition, they say that "the intrinsic value of soybean seed is in its supply of essential fatty acids and amino acids in the oil and protein, respectively;" and in this regard they report that Heagle *et al.* (1998) "observed a positive significant effect of CO<sub>2</sub> enrichment on soybean seed oil and oleic acid concentration."

Legumes and their responses to atmospheric CO<sub>2</sub> enrichment also figure prominently in a number of studies of *mixed* forage crops. In a study of nitrogen cycling in grazed pastures on the North Island of New Zealand, for example, Allard *et al.* (2003) report that under elevated CO<sub>2</sub>, leaves of the individual species exhibited lower nitrogen concentrations but higher water-



soluble carbohydrate (WSC) concentrations. They also say "there was a significantly greater proportion of legume in the diet at elevated CO<sub>2</sub>," and that this "shift in the botanical composition towards a higher proportion of legumes counterbalanced the nitrogen decrease observed at the single species scale, resulting in a nitrogen concentration of the overall diet that was unaffected by elevated CO<sub>2</sub>." What is more, they report that "changes at the species level and at the sward level appeared to combine additively in relation to WSC." Hence, they note that "as there was a significant correlation between WSC and digestibility (as previously observed by Dent and Aldrich, 1963 and Humphreys, 1989), there was also an increase in digestibility of the high CO<sub>2</sub> forage," which result, in their words, "matches that found in a Mini-FACE experiment under cutting (Teyssonneyre, 2002; Picon-Cochard *et al.*, 2004)," where "digestibility also increased in response to CO<sub>2</sub> despite reduced crude protein concentration." These data, plus the strong relationship between soluble sugars (rather than nitrogen) and digestibility, led them to suggest that "the widespread response to CO<sub>2</sub> of increased soluble sugars might lead to an increase in forage digestibility."

Luscher *et al.* (2004) found much the same thing in their review of the subject, which was based primarily on studies conducted at the Swiss FACE facility that hosts what has become the world's longest continuous atmospheric CO<sub>2</sub> enrichment study of a naturally-occurring grassland. In response to an approximate two-thirds increase in the air's CO<sub>2</sub> concentration, leaf nitrogen (N) concentrations of white clover (*Trifolium repens* L.) and perennial ryegrass (*Lolium perenne* L.) were reduced by 7% and 18%, respectively, when they were grown separately in pure stands. However, as Luscher *et al.* report, "the considerably lower concentration of N under elevated CO<sub>2</sub>, observed for *L. perenne* leaves in pure stands, was found to a much lesser extent for *L. perenne* leaves in the bi-species mixture with *T. repens* (Zanetti *et al.*, 1997; Hartwig *et al.*, 2000)." Furthermore, as they continue, "under elevated CO<sub>2</sub> the proportion of N-rich *T. repens* (40 mg N g<sup>-1</sup> dry matter) increased in the mixture at the expense of the N-poor *L. perenne* (24 mg N g<sup>-1</sup> dry matter when grown in monoculture)," the end result being that "the concentration of N in the harvested biomass of the mixture showed no significant reduction."

That this phenomenon is likely ubiquitous is suggested by the still more comprehensive review of the subject produced by Campbell *et al.* (2000), who analyzed research conducted between 1994 and 1999 by a worldwide network of 83 scientists associated with the Global Change and Terrestrial Ecosystems (GCTE) Pastures and Rangelands Core Research Project 1 (CRP1). This program had resulted in the publication of more than 165 peer-reviewed scientific journal articles; and Campbell *et al.* determined from this massive collection of data that the legume content of grass-legume swards was typically increased by approximately 10% in response to a doubling of the air's CO<sub>2</sub> content.

Also of interest within this context, Luscher *et al.* (2004) state that "the nutritive value of herbage from intensively managed grassland dominated by *L. perenne* and *T. repens* ... is well above the minimum range of the concentration of crude protein necessary for efficient digestion by ruminants (Barney *et al.* 1981)." Hence, they conclude that "a small decrease in the concentration of crude protein in intensively managed forage production systems [which

may never occur, as noted above] is not likely to have a negative effect on the nutritive value or on the intake of forage." In addition, in a CO<sub>2</sub>-enriched world of the future there would be much *more* such forage produced per unit of land and water devoted to the enterprise, clearly making the ongoing rise in the air's CO<sub>2</sub> content a big plus for animal husbandry.

One final forage study we have reviewed on our website is that of Newman *et al.* (2003), who investigated the effects of two levels of nitrogen fertilization and an approximate doubling of the air's CO<sub>2</sub> content on the growth and chemical composition of tall fescue (*Festuca arundinacea* Schreber cv. KY-31), both when infected and uninfected with a mutualistic fungal endophyte (*Neotyphodium coenophialum* Morgan-Jones and Gams). They found that the elevated CO<sub>2</sub> reduced the crude protein content of the forage by an average of 21% in three of the four situations studied: non-endophyte-infected plants in both the low and high nitrogen treatments, and endophyte-infected plants in the high nitrogen treatment. However, there was *no* protein reduction for endophyte-infected plants in the *low* nitrogen treatment.

This latter point is very important; for as noted by Newman *et al.*, "the endophyte is present in many native and naturalized populations and the most widely sown cultivars of *F. arundinacea*," so that the first two situations in which the CO<sub>2</sub>-induced protein reduction occurred (those involving non-endophyte-infected plants) *are not typical of the real world*. In addition, since the dry-weight biomass yield of the forage was increased by fully 53% under the low nitrogen regime, and since the *ten-times-greater* high nitrogen regime only boosted yields by an additional 8%, there would appear to be no need to apply any extra nitrogen to *F. arundinacea* in a CO<sub>2</sub>-enriched environment. Consequently, under best management practices in a doubled-CO<sub>2</sub> world of the future, little to no nitrogen would be added to the soil and there would be little to no reduction in the crude protein content of *F. arundinacea*, but there would be more than 50% more of it produced on the same amount of land.

With respect to the final plant quality studied by Newman *et al.*, i.e., forage digestibility, increasing soil nitrogen lowered *in vitro* neutral detergent fiber digestibility in both ambient and CO<sub>2</sub>-enriched air; and this phenomenon was most pronounced in the elevated CO<sub>2</sub> treatment. Again, however, under *low* nitrogen conditions there was *no* decline in plant digestibility. Hence, there is a *second* good reason to not apply extra nitrogen to *F. arundinacea* in a high CO<sub>2</sub> world of the future and, of course, little to no *need* to do so. Under best management practices in a future CO<sub>2</sub>-enriched atmosphere, therefore, the results of this study suggest that much greater quantities of good quality forage should be able to be produced without the addition of any -- or very little -- extra nitrogen to the soil.

But what about the *unmanaged world of nature*? Increases in the air's CO<sub>2</sub> content often - but not always (Goverde *et al.*, 1999) - lead to greater decreases in the concentrations of nitrogen and protein in the foliage of C<sub>3</sub> as compared to C<sub>4</sub> grasses (Wand *et al.*, 1999); and as a result, in the words of Barbehenn *et al.* (2004a), "it has been predicted that insect herbivores will increase their feeding damage on C<sub>3</sub> plants to a greater extent than on C<sub>4</sub> plants (Lincoln *et al.*, 1984, 1986; Lambers, 1993).

To test this hypothesis, Barbehenn *et al.* (2004a) grew *Lolium multiflorum* Lam. (Italian ryegrass, a common C<sub>3</sub> pasture grass) and *Bouteloua curtipendula* (Michx.) Torr. (sideoats gramma, a native C<sub>4</sub> rangeland grass) in chambers maintained at either the ambient atmospheric CO<sub>2</sub> concentration of 370 ppm or the doubled CO<sub>2</sub> concentration of 740 ppm for two months, after which newly-molted sixth-instar larvae of *Pseudaletia unipuncta* (a grass-specialist noctuid) and *Spodoptera frugiperda* (a generalist noctuid) were allowed to feed upon the grasses. As expected, foliage protein concentration decreased by 20% in the C<sub>3</sub> grass, but by only 1% in the C<sub>4</sub> grass, when grown in the CO<sub>2</sub>-enriched air. However, and "contrary to our expectations," according to Barbehenn *et al.*, "neither caterpillar species significantly increased its consumption rate to compensate for the lower concentration of protein in [the] C<sub>3</sub> grass," noting that "this result does not support the hypothesis that C<sub>3</sub> plants will be subject to greater rates of herbivory relative to C<sub>4</sub> plants in future [high-CO<sub>2</sub>] atmospheric conditions (Lincoln *et al.*, 1984)." In addition, and "despite significant changes in the nutritional quality of *L. multiflorum* under elevated CO<sub>2</sub>," they report that "no effect on the relative growth rate of either caterpillar species on either grass species resulted," and that there were "no significant differences in insect performance between CO<sub>2</sub> levels."

In a similar study with the same two plants, Barbehenn *et al.* (2004b) allowed grasshopper (*Melanoplus sanguinipes*) nymphs that had been reared to the fourth instar stage to feed upon the grasses; and once again, "contrary to the hypothesis that insect herbivores will increase their feeding rates disproportionately in C<sub>3</sub> plants under elevated atmospheric CO<sub>2</sub>," they found that "*M. sanguinipes* did not significantly increase its consumption rate when feeding on the C<sub>3</sub> grass grown under elevated CO<sub>2</sub>," suggesting that this observation implies that "post-ingestive mechanisms enable these grasshoppers to compensate for variable nutritional quality in their host plants," and noting that some of these post-ingestive responses may include "changes in gut size, food residence time, digestive enzyme levels, and nutrient metabolism (Simpson and Simpson, 1990; Bernays and Simpson, 1990; Hinks *et al.*, 1991; Zanotto *et al.*, 1993; Yang and Joern, 1994a,b)." In fact, their data indicated that *M. sanguinipes* growth rates may have actually *increased*, perhaps by as much as 12%, when feeding upon the C<sub>3</sub> foliage that had been produced in the CO<sub>2</sub>-enriched air.

In conclusion, with respect to both managed agricultural crops and the wild plants of earth's natural ecosystems, it would appear that the ongoing rise of the air's CO<sub>2</sub> concentration will have few negative impacts of any consequence on the nutritive value of their grains and foliage in terms of protein concentration. In fact, in tree crops such as citrus, CO<sub>2</sub>-induced changes in the activities of certain foliar proteins could well lead to vast increases in yield potential, as elucidated by the work of Idso *et al.* (2001).

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/p/protein.php>.

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#### 9.2.2.2.2. ANTIOXIDANT CONTENT

Environmental stresses induced by exposure to pollutants, drought, intense solar radiation and high air or water temperatures generate highly-reactive oxygenated compounds that damage plants. Ameliorating these stresses typically involves the production of antioxidant enzymes that scavenge and detoxify the highly-reactive oxygenated compounds. Hence, when stresses are present, concentrations and/or activities of antioxidants in plants are generally observed to be high; and as Lesser (1997) has noted in corals, they tend to counter the effects of the stress. A good question to ask, therefore, is how atmospheric CO<sub>2</sub> enrichment impacts this relationship and what the observed results imply.

In a study of two soybean genotypes, Pritchard *et al.* (2000) reported that three months' exposure to twice-ambient CO<sub>2</sub> concentrations reduced the activities of superoxide dismutase and catalase by an average of 23 and 39%, respectively. Likewise, Polle *et al.* (1997) showed that two years of atmospheric CO<sub>2</sub> enrichment reduced the activities of several key antioxidative enzymes, including catalase and superoxide dismutase, in beech seedlings. Moreover, Schwanz and Polle (1998) demonstrated that this phenomenon can persist indefinitely, as they discovered similar reductions in these same enzymes in mature oak trees that had been growing near natural CO<sub>2</sub>-emitting springs for 30 to 50 years.

The standard interpretation of these results is that the observed reductions in the activities of antioxidative enzymes under CO<sub>2</sub>-enriched conditions imply that plants exposed to higher-than-current atmospheric CO<sub>2</sub> concentrations experience less oxidative stress and thus have a reduced need for antioxidant protection. This conclusion further suggests that "CO<sub>2</sub>-advantaged" plants will be able to funnel more of their limited resources into the production of other plant tissues or processes essential to their continued growth and development.

On the other hand, when oxidative stresses do occur under high CO<sub>2</sub> conditions, the enhanced rates of photosynthesis and carbohydrate production resulting from atmospheric CO<sub>2</sub> enrichment generally enable plants to better deal with such stresses by providing more of the raw materials needed for antioxidant enzyme synthesis. Thus, when CO<sub>2</sub>-enriched sugar maple seedlings were subjected to an additional 200 ppb of ozone, Niewiadomska *et al.* (1999) reported that ascorbate peroxidase, which is the first line of enzymatic defence against ozone,

significantly increased. Likewise, Schwanz and Polle (2001) noted that poplar clones grown at 700 ppm CO<sub>2</sub> exhibited a much greater increase in superoxide dismutase activity upon chilling induction than clones grown in ambient air. In addition, Lin and Wang (2002) observed that activities of superoxide dismutase and catalase were much higher in CO<sub>2</sub>-enriched wheat than in ambiently-grown wheat following the induction of water stress.

Antioxidants are also of great importance to human health. In some cases, the additional carbon fixed during CO<sub>2</sub>-enrichment is invested in antioxidative compounds, rather than enzymes; and one of the most prominent of these plant products is *ascorbate* or vitamin C. In the early studies of Barbale (1970) and Madsen (1971, 1975), a tripling of the atmospheric CO<sub>2</sub> concentration produced a modest (7%) increase in this antioxidant in the fruit of tomato plants. Kimball and Mitchell (1981), however, could find no effect of a similar CO<sub>2</sub> increase on the same species, although the extra CO<sub>2</sub> of their study stimulated the production of vitamin A. In bean sprouts, on the other hand, a mere one-hour-per-day doubling of the atmospheric CO<sub>2</sub> concentration actually *doubled* plant vitamin C contents over a 7-day period (Tajiri, 1985).

Probably the most comprehensive investigation of CO<sub>2</sub> effects on vitamin C production in an agricultural plant -- a tree crop (sour orange) -- was conducted by Idso *et al.* (2002). In an atmospheric CO<sub>2</sub> enrichment experiment begun in 1987 and still ongoing, a 75% increase in the air's CO<sub>2</sub> content was observed to increase sour orange juice vitamin C concentration by approximately 5% in run-of-the-mill years when total fruit production was typically enhanced by about 80%. In aberrant years when the CO<sub>2</sub>-induced increase in fruit production was much greater, however, the increase in fruit vitamin C concentration was also greater, rising to a CO<sub>2</sub>-induced enhancement of 15% when fruit production on the CO<sub>2</sub>-enriched trees was 3.6 times greater than it was on the ambient-treatment trees.

These findings take on great significance when it is realized that scurvy -- which is induced by low intake of vitamin C -- may be resurgent in industrial countries, especially among children (Ramar *et al.*, 1993; Gomez-Carrasco *et al.*, 1994), and that subclinical scurvy symptoms are increasing among adults (Dickinson *et al.*, 1994). Furthermore, Hampl *et al.* (1999) have found that 12-20% of 12- to 18-year-old school children in the United States "drastically under-consume" foods that supply vitamin C; while Johnston *et al.* (1998) have determined that 12-16% of U.S. college students have marginal plasma concentrations of vitamin C. Hence, since vitamin C intake correlates strongly with the consumption of citrus juice (Dennison *et al.*, 1998), and since the only high-vitamin-C juice consumed in any quantity by children is orange juice (Hampl *et al.*, 1999), the modest role played by the ongoing rise in the air's CO<sub>2</sub> content in increasing the vitamin C concentration of orange juice could ultimately prove to be of considerable significance for public health in the United States and elsewhere.

Another important study to assess the impact of elevated levels of atmospheric CO<sub>2</sub> on plant antioxidant production was that of Wang *et al.* (2003), who evaluated the effects of elevated CO<sub>2</sub> on the antioxidant activity and flavonoid content of strawberry fruit in field plots at the U.S. Department of Agriculture's Beltsville Agricultural Research Center in Beltsville, Maryland, where they grew strawberry plants (*Fragaria x ananassa* Duchesne cv. Honeoye) in six clear-



acrylic open-top chambers, two of which were maintained at the ambient atmospheric CO<sub>2</sub> concentration, two of which were maintained at ambient + 300 ppm CO<sub>2</sub>, and two of which were maintained at ambient + 600 ppm CO<sub>2</sub> for a period of 28 months (from early spring of 1998 through June 2000). The scientists harvested the strawberry fruit, in their words, "at the commercially ripe stage" in both 1999 and 2000, after which they analyzed them for a number of different antioxidant properties and flavonol contents.

Before reporting what they found, Wang *et al.* provide some background by noting that "strawberries are good sources of natural antioxidants (Wang *et al.*, 1996; Heinonen *et al.*, 1998)." They further report that "in addition to the usual nutrients, such as vitamins and minerals, strawberries are also rich in anthocyanins, flavonoids, and phenolic acids," and that "strawberries have shown a remarkably high scavenging activity toward chemically generated radicals, thus making them effective in inhibiting oxidation of human low-density lipoproteins (Heinonen *et al.*, 1998)." In this regard, they note that previous studies (Wang and Jiao, 2000; Wang and Lin, 2000) "have shown that strawberries have high oxygen radical absorbance activity against peroxy radicals, superoxide radicals, hydrogen peroxide, hydroxyl radicals, and singlet oxygen." In their experiment, therefore, they were essentially seeking to see if atmospheric CO<sub>2</sub> enrichment could make a good thing even better.

So what did the Agricultural Research Service scientists find? They determined, first of all, that strawberries had higher concentrations of ascorbic acid (AsA) and glutathione (GSH) "when grown under enriched CO<sub>2</sub> environments." In going from ambient to ambient + 300 ppm CO<sub>2</sub> and ambient + 600 ppm CO<sub>2</sub>, for example, AsA concentrations increased by 10 and 13%, respectively, while GSH concentrations increased by 3 and 171%, respectively. They also learned that "an enriched CO<sub>2</sub> environment resulted in an increase in phenolic acid, flavonol, and anthocyanin contents of fruit." For nine different flavonoids, for example, there was a mean concentration increase of  $55 \pm 23\%$  in going from the ambient atmospheric CO<sub>2</sub> concentration to ambient + 300 ppm CO<sub>2</sub>, and a mean concentration increase of  $112 \pm 35\%$  in going from ambient to ambient + 600 ppm CO<sub>2</sub>. In addition, they report that the "high flavonol content was associated with high antioxidant activity." As for the significance of these findings, Wang *et al.* note that "anthocyanins have been reported to help reduce damage caused by free radical activity, such as low-density lipoprotein oxidation, platelet aggregation, and endothelium-dependent vasodilation of arteries (Heinonen *et al.*, 1998; Rice-Evans and Miller, 1996)."

In summarizing their findings, Wang *et al.* say "strawberry fruit contain flavonoids with potent antioxidant properties, and under CO<sub>2</sub> enrichment conditions, increased the[ir] AsA, GSH, phenolic acid, flavonol, and anthocyanin concentrations," further noting that "plants grown under CO<sub>2</sub> enrichment conditions also had higher oxygen radical absorbance activity against [many types of oxygen] radicals in the fruit." Hence, they determined that atmospheric CO<sub>2</sub> enrichment truly did "make a good thing better."

We note additionally in this regard that elevated levels of atmospheric CO<sub>2</sub> also make *more* of that good thing. Deng and Woodward (1998), for example, report that after growing

strawberry plants in air containing an additional 170 ppm of CO<sub>2</sub>, total fresh fruit weights were 42 and 17% greater than weights displayed by control plants grown at high and low soil nitrogen contents, respectively; while Bushway and Pritts (2002) report that a two- to three-fold increase in the air's CO<sub>2</sub> content boosted strawberry fruit yield by an average of 62%. In addition, Campbell and Young (1986), Keutgen *et al.* (1997), and Bunce (2001) report positive strawberry photosynthetic responses to an extra 300 ppm of CO<sub>2</sub> ranging from 9% to 197% (mean of 76% ± 15%); and Desjardins *et al.* (1987) report a 118% increase in photosynthesis in response to a 600 ppm increase in the air's CO<sub>2</sub> concentration.

Other researchers have found similar enhancements of antioxidative compounds under enriched levels of atmospheric CO<sub>2</sub>. Estiarte *et al.* (1999), for example, reported that a 180-ppm increase in the air's CO<sub>2</sub> content increased the foliar concentrations of flavonoids, which protect against UV-B radiation damage, in field-grown spring wheat by 11 to 14%. Caldwell *et al.* (2005), on the other hand, found that an ~75% increase in the air's CO<sub>2</sub> content increased the total isoflavone content of soybean seeds by 8% when the air temperature during seed fill was 18°C, by 104% when the air temperature during seed fill was 23°C, by 101% when the air temperature was 28°C, and by 186% and 38%, respectively, when a drought-stress treatment was added to the latter two temperature treatments. Lastly, in an experiment conducted under *very high* atmospheric CO<sub>2</sub> concentrations, Ali *et al.* (2005) found that CO<sub>2</sub> levels of 10,000 ppm, 25,000 ppm and 50,000 ppm increased total flavonoid concentrations of ginseng roots by 228%, 383% and 232%, respectively, total phenolic concentrations by 58%, 153% and 105%, cysteine contents by 27%, 65% and 100%, and non-protein thiol contents by 12%, 43% and 62%, all of which substances are potent antioxidants. What is more, it is interesting to note that the increased consumption of such plant material - naturally enriched with antioxidative compounds as a consequence of the historical rise in the air's CO<sub>2</sub> content - may have played a role in the observed decline in human mortality rates over the period 1950-1994 (Tuljapurkar *et al.*, 2000).

In summary, as the CO<sub>2</sub> content of the air rises, plants typically experience less oxidative stress; and since they thus need fewer antioxidants for protection, antioxidant levels in their leaves decline, which enables them to use more of their valuable resources for other important purposes. However, when oxidative stresses are present, elevated CO<sub>2</sub> helps to increase the synthesis and activities of antioxidants that tend to alleviate the problems the stresses cause. Moreover, the possibility exists that the greater concentrations of antioxidative compounds in plant tissues caused by the historical rise in the air's CO<sub>2</sub> content may have contributed to the human life span extension experienced over the course of the Industrial Revolution.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/a/antioxidants.php>.

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### 9.2.3. Medicinal Constituents of Plants

Primitive medical records indicate that extracts from many species of plants have been used for treating a variety of human health problems for perhaps the past 3500 years (Machlin, 1992; Pettit *et al.*, 1993, 1995). In modern times the practice has continued, with numerous chemotherapeutic agents being isolated (Gabrielsen *et al.*, 1992a). Until recently, however, no studies had investigated the effects of atmospheric CO<sub>2</sub> enrichment on specific plant compounds of direct medicinal value.

This situation changed when Stuhlfauth *et al.* (1987) studied the individual and combined effects of atmospheric CO<sub>2</sub> enrichment and water stress on the production of secondary metabolites in the woolly foxglove (*Digitalis lanata* EHRH), which produces the cardiac glycoside *digoxin* that is used in the treatment of cardiac insufficiency. Under controlled well-watered conditions in a phytotron, a near-tripling of the air's CO<sub>2</sub> content increased plant dry weight production in this medicinal plant by 63%, while under water-stressed conditions the CO<sub>2</sub>-induced dry weight increase was 83%. In addition, the *concentration* of digoxin within the plant dry mass was enhanced by 11% under well-watered conditions and by 14% under conditions of water stress.

In a subsequent whole-season field experiment, Stuhlfauth and Fock (1990) obtained similar results. A near-tripling of the air's CO<sub>2</sub> concentration led to a 75% increase in plant dry weight production per unit land area and a 15% increase in digoxin yield per unit dry weight of plant, which combined to produce an actual doubling of total digoxin yield per hectare of cultivated land.

Equally impressive was the study of Idso *et al.* (2000), who evaluated the response of the tropical spider lily (*Hymenocallis littoralis* Jacq. Salisb.) to elevated levels of atmospheric CO<sub>2</sub> over four growing seasons. This plant has been known since ancient times to possess anti-tumor activity; and in modern times it has been shown to contain constituents that are effective against lymphocytic leukemia and ovary sarcoma (Pettit *et al.*, 1986). These same plant constituents have also been proven to be effective against the U.S. National Cancer Institute's panel of 60 human cancer cell lines, demonstrating greatest effectiveness against melanoma, brain, colon, lung and renal cancers (Pettit *et al.*, 1993). In addition, it exhibits strong anti-viral activity against Japanese encephalitis and yellow, dengue, Punta Tora and Rift Valley fevers (Gabrielsen *et al.*, 1992a,b).

Idso *et al.* determined that a 75% increase in the air's CO<sub>2</sub> concentration produced a 56% increase in the spider lily's belowground bulb biomass, where the disease-fighting substances are found. In addition, for these specific substances, they observed a 6% increase in the concentration of a two-constituent (1:1) mixture of 7-deoxynarciclasine and 7-deoxy-trans-dihydronarciclasine, an 8% increase in pancratistatin, an 8% increase in trans-dihydronarciclasine, and a 28% increase in narciclasine. Averaged together and combined with the 56% increase in bulb biomass, these percentage concentration increases resulted in a total mean active-ingredient increase of 75% for the plants grown in air containing 75% more CO<sub>2</sub>.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/h/co2healthpromoting.php>.

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#### 9.2.4. Other Plant Constituents

A number of other plant constituents also perform important functions in maintaining human health, including sugars, lipids, oils and fatty acids, as well as macro- and micro-nutrients. Although concerns have been raised about the availability of certain of the latter elements in plants growing in a CO<sub>2</sub>-enriched world (Loladze, 2002), the jury is still out with respect to this subject as a consequence of the paucity of pertinent data. Literally thousands of studies have assessed the impact of elevated levels of atmospheric CO<sub>2</sub> on the *quantity* of biomass produced by agricultural crops, but only a tiny fraction of that number have looked at any aspect of food *quality*. From what has been learned about plant protein, antioxidants and the few medicinal substances that have been investigated in this regard, however, there is no reason to believe that these other plant constituents would be present in any *lower* concentrations in a CO<sub>2</sub>-enriched world of the future than they are currently. Indeed, there is ample evidence to suggest they may well be present in significantly *greater* concentrations, and *certainly* in greater *absolute amounts*.

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### **9.3. A Brief History Of Human Longevity**

The past two centuries have witnessed a significant degree of global warming, as the earth has recovered from the global chill of the Little Ice Age and entered the Modern Warm Period. Simultaneously, the planet has seen an increase in its atmospheric CO<sub>2</sub> concentration that has taken it to levels not experienced for eons. What effects have these "twin evils" of the climate-alarmist crowd had on human health? Although no one can give a precise quantitative answer to this question, it is possible to assess their *relative* importance by considering the history of human longevity.

Tuljapurkar *et al.* (2000) examined mortality over the period 1950-1994 in Canada, France, Germany (excluding the former East Germany), Italy, Japan, the United Kingdom, and the United States, finding that "in every country over this period, mortality at each age has declined exponentially at a roughly constant rate." In discussing these findings, Horiuchi (2000) notes that the average lifespan of early humans was approximately 20 years, but that in the major industrialized countries it is now about 80 years, with the bulk of this increase having come in the past 150 years. He then notes that "it was widely expected that as life expectancy became very high and approached the 'biological limit of human longevity,' the rapid 'mortality decline' would slow down and eventually level off," but he states the now obvious fact that "such a deceleration has not occurred."

"These findings give rise to two interrelated questions," says Horiuchi: (1) "Why has mortality decline not started to slow down?" and (2) "Will it continue into the future?"

Some points to note in attempting to answer these questions are the following. First, in Horiuchi's words, "in the second half of the nineteenth century and the first half of the twentieth century, there were large decreases in the number of deaths from infectious and parasitic diseases, and from poor nutrition and disorders associated with pregnancy and childbirth," which led to large reductions in the deaths of infants, children and young adults. In the second half of the twentieth century, however, Horiuchi notes that "mortality from degenerative diseases, most notably heart diseases and stroke, started to fall," and the reduction was most pronounced among the elderly. Some suspected that this latter drop in mortality might have been achieved "through postponing the deaths of seriously ill people," but data from the United States demonstrate, in his words, that "the health of the elderly greatly improved in the 1980s and 1990s, suggesting that the extended length of life in old age is mainly due to better health rather than prolonged survival in sickness."

Providing additional support for this conclusion is the study of Manton and Gu (2001). With the completion of the latest of the five National Long-Term Care Surveys of disability in U.S. citizens



over 65 years of age -- which began in 1982 and extended to 1999 at the time of the writing of their paper -- these researchers were able to discern two most interesting trends: (1) disabilities in this age group decreased over the entire period studied, and (2) disabilities decreased at a rate that grew ever larger with the passing of time.

Specifically, over the entire 17-year period of record, there was an amazing relative decline in chronic disability of 25%, as the percentage of the over-65-years-of-age group that was disabled dropped from 26.2% in 1982 to 19.7% in 1999. What is more, the percentage disability decline rate per year for the periods 1982-1989, 1989-1994 and 1994-1999 was 0.26, 0.38 and 0.56% per year, respectively. Commenting on the ever-accelerating nature of this disability decline, the authors say "it is surprising, given the low level of disability in 1994, that the rate of improvement accelerated" over the most recent five-year interval.

With respect to the population of the entire planet, Oeppen and Vaupel (2002) report that "world life expectancy more than doubled over the past two centuries, from roughly 25 years to about 65 for men and 70 for women." What is more, they note that "for 160 years, best-performance life expectancy has steadily increased by a quarter of a year per year," and they emphasize that this phenomenal trend "is so extraordinarily linear that it may be *the most remarkable regularity of mass endeavor ever observed* [our italics]."

These observations clearly demonstrate that if the increases in air temperature and CO<sub>2</sub> concentration of the past two centuries were indeed bad for our health, their combined negative influence was *miniscule* compared to whatever else was at work in promoting this vast increase in worldwide human longevity; and it is that "whatever else" to which we now turn our attention.

To summarize to this point, in countries with highly developed market economies where good health care is readily available, deaths of infants, children and young adults have been dramatically reduced over the last century or so, to the point where average life expectancy is now largely determined by what happens to elderly people; and it is evident that under these circumstances, the elderly are living ever longer with the passing of time. It is further evident that this phenomenon is likely due to ever-improving health in older people, which in turn is likely the result of continuing improvements in the abilities of their bodies to repair cellular damage caused by degenerative processes associated with old age, i.e., stresses caused by the reactive oxygen species that are generated by normal metabolism (Finkel and Holbrook, 2000). What is responsible for this incredible lengthening of human life span? It is probably a number of things acting in concert, with no single phenomenon overpowering the others. Nevertheless, the multi-faceted force has operated with unwavering consistency since the inception of the Industrial Revolution, which leads us to wonder if the "twin evils" of the climate-alarmist crowd might actually be responsible for some portion of the longer and healthier lives that are being experienced by the planet's elderly. In what follows we briefly review some materials that illustrate some of the means by which elevated atmospheric CO<sub>2</sub> concentrations may help to extend human life span.

Wentworth *et al.* (2003) report they found "evidence for the production of ozone in human disease," specifically noting that "signature products unique to cholesterol ozonolysis are present within atherosclerotic tissue at the time of carotid endarterectomy, suggesting that ozone production occurred during lesion development." As Marx (2003) describes it, "researchers think that inflammation of blood vessels is a major instigator of plaque formation," that "ozone contributes to plaque formation by oxidizing cholesterol," and that the new findings "suggest new strategies for preventing atherosclerosis." Further, according to Marx, Daniel Steinberg of the University of California, San Diego, says that although it's still too early to definitively state whether ozone production in plaques is a major contributor to atherosclerosis, he expresses his confidence that once we know for sure, we'll know which antioxidants will work in *suppressing* plaque formation.

Reactive oxygen species (ROS) generated during cellular metabolism or peroxidation of lipids and proteins also play a causative role in the pathogenesis of cancer, along with coronary heart disease (CHD), as demonstrated by Slaga *et al.* (1987), Frenkel (1992), Marnett (2000), Zhao *et al.* (2000) and Wilcox *et al.* (2004). However, as noted by Yu *et al.* (2004), "antioxidant treatments may terminate ROS attacks and reduce the risks of CHD and cancer, as well as other ROS-related diseases such as Parkinson's disease (Neff, 1997; Chung *et al.*, 1999; Wong *et al.*, 1999; Espin *et al.*, 2000; Merken and Beecher, 2000)." As a result, they say that "developing functional foods rich in natural antioxidants may improve human nutrition and reduce the risks of ROS-associated health problems."

Consider, in this regard, the common strawberry. Wang *et al.* (2003) report that strawberries are especially good sources of natural antioxidants. They say that "in addition to the usual nutrients, such as vitamins and minerals, strawberries are also rich in anthocyanins, flavonoids, and phenolic acids," and that "strawberries have shown a remarkably high scavenging activity toward chemically generated radicals, thus making them effective in inhibiting oxidation of human low-density lipoproteins (Heinonen *et al.*, 1998)." They also note that Wang and Jiao (2000) and Wang and Lin (2000) "have shown that strawberries have high oxygen radical absorbance activity against peroxy radicals, superoxide radicals, hydrogen peroxide, hydroxyl radicals, and singlet oxygen." And they say that "anthocyanins have been reported to help reduce damage caused by free radical activity, such as low-density lipoprotein oxidation, platelet aggregation, and endothelium-dependent vasodilation of arteries (Heinonen *et al.*, 1998; Rice-Evans and Miller, 1996)."

Our reason for citing all of this information is that Wang *et al.* (2003) have recently demonstrated that enriching the air with carbon dioxide increases both the concentrations and activities of many of these helpful substances. They determined, for example, that strawberries had higher concentrations of ascorbic acid and glutathione when grown in CO<sub>2</sub>-enriched environments. They also learned that "an enriched CO<sub>2</sub> environment resulted in an increase in phenolic acid, flavonol, and anthocyanin contents of fruit." For nine different flavonoids, in fact, there was a mean concentration increase of 55% in going from the ambient atmospheric CO<sub>2</sub> concentration to ambient + 300 ppm CO<sub>2</sub>, and a mean concentration increase of 112% in

going from ambient to ambient + 600 ppm CO<sub>2</sub>. Also, they report that "high flavonol content was associated with high antioxidant activity."

There is little reason to doubt that similar concentration and activity increases in the same and additional important phytochemicals in other food crops would occur in response to the same increases in the air's CO<sub>2</sub> concentration. Indeed, the *aerial fertilization effect* of atmospheric CO<sub>2</sub> enrichment is a near-universal phenomenon that operates among plants of all types, *and it is very powerful*. Since the dawning of the Industrial Revolution, for example, the work of Mayeux *et al.* (1997) and Idso and Idso (2000) suggests that the concomitant historical increase in the air's CO<sub>2</sub> content has led to mean yield increases of approximately 70% in C<sub>3</sub> cereals, 28% in C<sub>4</sub> cereals, 33% in fruits and melons, 62% in legumes, 67% in root and tuber crops, and 51% in vegetables. Hence, there must have been significant concomitant increases in the concentrations and activities of the various phytochemicals in these foods that act as described by Wang *et al.* (2003).

Our reason for reporting these observations is that atmospheric CO<sub>2</sub> enrichment has been documented to enhance the concentrations of a number of antioxidants in many of the foods we eat. In what follows, therefore, we merely report the results of two studies that have confirmed the positive effects of antioxidant-induced decreases in animal ROS concentrations on animal life span.

Melov *et al.* (2000) tested the theory that reactive oxygen species cause aging by examining the effects of two superoxide dismutase-/catalase-like mimetics (EUK-8 and EUK-134) on the life-span of normal and mutant *Caenorhabditis elegans* worms that ingested various concentrations of the mimetics. In all of their experiments, treatment of normal worms with the antioxidant mimetics significantly increased both mean and maximum life-span. Treatment of normal worms with but 0.05 mM EUK-134, for example, increased their mean life-span by fully 54%; and in mutant worms whose life-span had been genetically shortened by 37%, treatment with 0.5 mM EUK-134 restored their life-span to normal by increasing their mutation-reduced life-span by 67%. It was also determined that these effects were not due to a reduction in worm metabolism, which could have reduced the production of oxygen radicals, but "by augmenting natural antioxidant defenses without having any overt effects on other traits." In other words, in the words of the authors, "these results suggest that endogenous oxidative stress is a major determinant of the rate of aging," the significance of which statement resides in the fact that antioxidants tend to reduce such stresses in animals, including man, and in the observation that atmospheric CO<sub>2</sub> enrichment has been shown to significantly enhance the concentrations of many of these important ROS-fighting constituents of the foods we eat.

Another study to address the subject was conducted by Larsen and Clarke (2002), who fed diets with and without coenzyme Q to wild-type *Caenorhabditis elegans* and several mutants during the adult phases of their lives, while they recorded the lengths of time they survived. This work revealed that "withdrawal of coenzyme Q from the diet of wild-type nematodes extends adult life-span by ~60%." In addition, they found that the life-spans of the four different mutants they studied were extended by a Q-less diet. More detailed experiments led them to conclude that

the life-span extensions were due to *reduced generation* and/or *increased scavenging* of reactive oxygen species, leading them to conclude in the final sentence of their paper that "the combination of reduced generation and increased scavenging mechanisms are predicted to result in a substantial decrease in the total cellular ROS and thereby allow for an extended life-span."

In light of these many diverse observations of both plants and animals, there is ample reason to believe that the historical increase in the air's CO<sub>2</sub> content has played a prominent role in enhancing many aspects of human health over the course of the Industrial Revolution, and that its continued upward trend will provide ever more of the same benefits, not the least of which is *increased longevity*. Consequently, we end this section with the encouraging thought that perhaps the best way to obtain these benefits is to directly consume foods that are known to contain high levels of antioxidants, i.e., fruits and vegetables, since with each passing year these foods will likely contain ever greater concentrations of ROS-fighting substances, thanks to the ongoing rise in the air's CO<sub>2</sub> content that comes primarily from the burning of fossil fuels.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/h/humanlifespan.php>.

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#### **9.4. Conclusions**

Although historical and projected future increases in the air's CO<sub>2</sub> concentration and its wrongly-predicted ability to lead to catastrophic global warming have been universally hailed by climate alarmists as diabolically detrimental to human health, scientific studies clearly demonstrate that such is not the case. Throughout the entire course of the Industrial Revolution, during which time the air's CO<sub>2</sub> content rose by 35% and its near-surface temperature by about 1°C, there has been not the slightest negative impact on human lifespan. In fact, human lifespan has concurrently experienced an almost unbelievable increase that shows no sign of ultimately leveling off or even slowing down. What is more, warming has been shown to positively impact human health, while atmospheric CO<sub>2</sub> enrichment has been shown to enhance the health-promoting properties of the food we eat (as well as produce more of it) and increase the presence and effectiveness of disease-fighting substances found in plants. Clearly, we have absolutely nothing to fear from the "twin evils" (CO<sub>2</sub> and warming) of the extreme environmental movement. Indeed, they would appear to be our *friends*.

## 10. ADDITIONAL CONSIDERATIONS

In our final chapter, we discuss a *non*-climatic catastrophe that a cadre of particularly insightful researchers have found to be looming ominously on the horizon, but about which much less is typically said or written, although it represents a more *realistic*, more *immediate*, and more *dangerous* threat to the well-being of man and nature alike than that of speculative CO<sub>2</sub>-induced global warming. And ironically, what many people believe to be the *source* of current global warming – rising anthropogenic CO<sub>2</sub> emissions – is actually our *last best hope* to avoid this very real threat.

### **10.1. Feeding Humanity and Saving Nature**

*How much land can ten billion people spare for nature?* This provocative question was first posed by America's Paul Waggoner in the title of an insightful 1995 essay, wherein he explored the dynamic tension that exists between the need for land to support the agricultural enterprises that sustain mankind, and the need for land to support the natural ecosystems that sustain all other creatures (Waggoner, 1995). This challenge of meeting our future food needs – and not decimating the rest of the biosphere in the process – was stressed even more strongly in the 8 August 2002 issue of *Nature* (Huang *et al.*, 2002), where Jikun Huang of the Chinese Academy of Sciences and two US colleagues wrote that we humans “have encroached on almost all of the world's frontiers, leaving little new land that is cultivatable.” And in consequence of humanity's ongoing usurpation of this most basic of natural resources, Peter H. Raven stated in his Presidential Address to the American Association for the Advancement of Science – which was published in *Science* (Raven, 2002) just one day after Huang *et al.*'s report appeared in *Nature* – that “species-area relationships, taken worldwide in relation to habitat destruction, lead to projections of the loss of fully two-thirds of all species on earth by the end of this century.”

If one were to pick the most significant threat currently facing the biosphere, this would likely be it: a single species of life, *Homo sapiens*, is on course to *completely annihilate* fully two-thirds of the ten million or so other species with which we share the planet, and to do so within less than a century, simply by appropriating the land and water resources that support all other species and using it to sustain ourselves.

In comparison, the predicted dire consequences of potential CO<sub>2</sub>-induced global warming fade into insignificance, in terms of both magnitude and immediacy, as well as in their likelihood of occurrence. Also, as shown in the preceding chapters, the root cause of 20<sup>th</sup>-century global warming is hotly debated; and plans to thwart its continuance are incredibly difficult, if not impossible, to define and implement. In addition, what many people believe to be the *source* of current global warming – rising anthropogenic CO<sub>2</sub> emissions – is actually our *last best hope* to preserve land for nature, a point to which we shall return shortly.

In a more detailed analysis of the impending “global land-grab” catastrophe – which moved it closer to the present by a full half-century – ten highly-respected researchers led by the University of Minnesota’s David Tilman wrote in the 13 April 2001 issue of *Science* (Tilman *et al.*, 2001) that the task of meeting the doubled global food demand, which they calculated would exist in the year 2050, would likely exact a toll that “may rival climate change in environmental and societal impacts.” But how could something so catastrophic manifest itself so soon?

Tilman and his nine collaborators shed some light on this question by noting that at the end of the last century mankind was already appropriating “more than a third of the production of terrestrial ecosystems and about half of usable freshwaters.” Now, think of *doubling* those figures, in order to meet the doubled global food demand Tilman *et al.* predict for the year 2050. The results suggest that a mere four decades from now mankind will be appropriating *more than two thirds* of terrestrial ecosystem production and essentially *all of the usable freshwater on the face of the planet*, a point that has also been discussed in depth by the UK’s J.S. Wallace (Wallace, 2000).

In terms of *land* devoted to agriculture, Tilman *et al.* calculate a much less ominous 18% increase by the year 2050. However, because most developed countries are projected to withdraw large areas of land from farming over the next fifty years, the loss of natural ecosystems to crops and pastures in developing countries will amount to about half of their remaining suitable land, which would, in the words of the Tilman team, “represent the worldwide loss of natural ecosystems larger than the United States.” What is more, they say that these land usurpations “could lead to the loss of about a third of remaining tropical and temperate forests, savannas, and grasslands.” And in a worrisome reflection upon the consequences of these land-use changes, they remind us that “species extinction is an irreversible impact of habitat destruction.”

What, if anything, can be done to avoid this horrific situation? In a subsequent analysis that was published in the 8 August 2002 issue of *Nature* (Tilman *et al.*, 2002), Tilman and a second set of collaborators introduced a few more facts before suggesting some solutions. They noted, for example, that by 2050 the human population of the globe is projected to be 50% larger than it was just prior to the time of their writing, and that global grain demand by 2050 could well double, due to expected increases in per capita real income and dietary shifts toward a higher proportion of meat. Hence, they but stated the obvious when they concluded that “raising yields on existing farmland is essential for ‘saving land for nature’.”

So how can this readily-defined but Herculean task be accomplished? Tilman *et al.* proposed a strategy that focuses on three essential efforts: (1) increasing crop yield per unit of *land area*, (2) increasing crop yield per unit of *nutrients applied*, and (3) increasing crop yield per unit of *water used*.

With respect to the first of these efforts – increasing crop yield per unit of land area – the researchers note that in many parts of the world the historical rate-of-increase in crop yield is declining, as the genetic ceiling for maximal yield potential is being approached. This



observation, in their estimation, “highlights the need for efforts to steadily increase the yield potential ceiling.” With respect to the second effort – increasing crop yield per unit of nutrients applied – they note that “without the use of synthetic fertilizers, world food production could not have increased at the rate [that it did in the past] and more natural ecosystems would have been converted to agriculture.” Hence, they say that the ultimate solution “will require significant increases in nutrient use efficiency, that is, in cereal production per unit of added nitrogen.” Finally, with respect to the third effort – increasing crop yield per unit of water used – Tilman *et al.* note that “water is regionally scarce,” and that “many countries in a band from China through India and Pakistan, and the Middle East to North Africa either currently or will soon fail to have adequate water to maintain per capita food production from irrigated land.” Increasing crop water use efficiency, therefore, is also a must.

Although the impending *humanity vs. nature* crisis and several important elements of its potential solution are thus well defined, Tilman and his first set of collaborators concluded that “even the best available technologies, fully deployed, cannot prevent many of the forecasted problems.” This was also the finding of a study we conducted a few years ago (Idso and Idso, 2000), wherein we concluded that although “expected advances in agricultural technology and expertise will significantly increase the food production potential of many countries and regions,” these advances “will not increase production fast enough to meet the demands of the even faster-growing human population of the planet.”

So how can we prevent this unthinkable catastrophe from occurring, especially when it has been concluded by highly adept individuals that the earth possesses insufficient land and freshwater resources to forestall it, while simultaneously retaining any semblance of the natural world and its myriad animate creations? Although the task may appear next to impossible to accomplish, *it can be done*; for we have a powerful ally in the ongoing rise in the atmosphere’s CO<sub>2</sub> concentration, which *can provide* what we can’t.

Since atmospheric CO<sub>2</sub> is the basic “food” of nearly all plants, the more of it there is in the air, the better they function and the more productive they become. As discussed in Chapter 6, for a 300-ppm (part per million) increase in the atmosphere’s CO<sub>2</sub> concentration above the planet’s current base level of slightly less than 400 ppm, for example, the productivity of earth’s herbaceous plants rises by 30 to 50% (Kimball, 1983; Idso and Idso, 1994), while the productivity of its woody plants rises by 50 to 80% (Saxe et al., 1998; Idso and Kimball, 2001). Consequently, as the air’s CO<sub>2</sub> content continues to rise, so too will the productive capacity or *land-use efficiency* of the planet continue to rise, as the aerial fertilization effect of the upward-trending atmospheric CO<sub>2</sub> concentration boosts the growth rates and biomass production of nearly all plants in nearly all places. In addition, elevated concentrations of atmospheric CO<sub>2</sub> typically increase plant *nutrient-use efficiency* in general – and all-important *nitrogen-use efficiency* in particular – as well as plant *water-use efficiency*. Consequently, with respect to fostering all three of the major efforts Tilman *et al.* (2002) say are needed to prevent the catastrophic consequences they foresee for the planet just a few decades from now, a continuation of the historical upward trend in the air’s CO<sub>2</sub> content would appear to be, in common parlance, “just what the doctor ordered.”

In the specific case we are considering here, the degree of crop yield enhancement likely to be provided by the increase in atmospheric CO<sub>2</sub> concentration expected to occur between 2000 and 2050 has been calculated by Idso and Idso (2000) to be sufficient – but just barely – to compensate for the huge differential expected to otherwise prevail between the supply and demand for food some four decades from now. Consequently, letting the evolution of technology take its *natural* course, with respect to anthropogenic CO<sub>2</sub> emissions, would appear to be the only way we will ever be able to grow enough food to support ourselves in the year 2050 without taking unconscionable amounts of land and freshwater resources from nature and decimating the biosphere in the process.

In spite of the dilemma described above, many have called for the implementation of strict measures to reduce anthropogenic CO<sub>2</sub> emissions. So, how does society proceed in this situation – positioned (as we are) between (as it were) *a rock and a hard place*? We believe that the logical route to take is to carefully consider the *relative reliabilities* of the predictive techniques that are used to derive the two very different catastrophes the two sides of the debate are claiming will occur if the measures they propose are not adopted.

In the case of catastrophic CO<sub>2</sub>-induced global warming, the end result is derived from mathematical models of earth's global climate system, as it is currently understood. In the case of the catastrophic imbalance between global food supply and demand, the end result is derived from mathematical models of human population growth and projected increases in agricultural productivity, as these phenomena are currently understood. In thinking about these different models, and the subsets of component processes that comprise them, it is our belief that projections of human population growth and agricultural productivity just four decades into the future are *far* more likely to be correct than are predictions of earth's climatic state over the next several centuries. In addition to the obvious time differential between the two sets of predictions, human population growth and agricultural productivity are much better-understood processes than is global climate change, which involves a host of complex phenomena that span a spatial scale of fully *fourteen orders of magnitude*, ranging from the planetary scale of 10<sup>7</sup> meters to the cloud microphysical scale of 10<sup>-6</sup> meter. What is more, many of the component processes that comprise today's state-of-the art climate models are far from adequately understood (see Chapter 2), even to the extent that the very *signs* of their impacts on global temperature change (whether positive or negative) are in many cases *not yet known*. Consequently, in light of the much greater confidence that can realistically be vested in demographic and agricultural production models, it would seem that much greater credence can be placed in their predictions than in the predictions of climate models.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/f/food.php>.

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### **10.2. Biofuels: A Solution or a Problem?**

In an interview that he gave to *Physics Today*, which was published in the magazine's September 2007 issue (Feder, 2007), Sir John Houghton declared that "we need very large growth in renewable energy sources," among which he listed *biomass* -- as in *biofuels* -- in second place after *solar*. Already, however, it has become abundantly clear to researchers around the world that meeting this so-called "need" is not without potential problems of its own.

In a study published online in the journal *Climatic Change* on 15 February 2007, two scientists (Johansson and Azar, 2007) analyzed what they called the "food-fuel competition for bio-productive land," developing in the process "a long-term economic optimization model of the U.S. agricultural and energy system," wherein they found that the competition for land to grow crops for both food and fuel production leads to a situation where, in their words, "prices for all crops as well as animal products increase substantially." In fact, in the May/June 2007 issue of *Foreign Affairs*, two other researchers (Runge and Senauer, 2007) reported that the production of corn-based ethanol in the United States *already*, as they describe it, "takes so much supply to keep ethanol production going that the price of corn -- and those of other food staples -- is shooting up around the world." And to put the situation in a perspective to which most Americans can readily relate, they noted that "filling the 25-gallon tank of an SUV with pure ethanol requires over 450 pounds of corn -- which contains enough calories to feed one person for a year."

But not only does biofuel production reduce the ability of the world's poor to purchase the food they so desperately need to sustain themselves, it also does *irreparable harm* to what we could call "wild nature," as native plants and animals lose ever more habitat and freshwater resources to the biofuels industry, which is rapidly advancing the time of their ultimate disappearance from the face of the earth, as they are inexorably driven to extinction.

Additional support for this view is provided by an article in the 17 August 2007 issue of *Science*, where another pair of researchers (Righelato and Spracklen, 2007) wrote that using ethanol derived from crops as a substitute for gasoline and vegetable oils in place of diesel fuel "would require very large areas of land in order to make a significant contribution to mitigation of fossil fuel emissions and would, directly or indirectly, put further pressure on natural forests and grasslands." As an example of this unfortunate fact, the two British scientists calculated that a 10% substitution of biofuels for petrol and diesel fuel would require "43% and 38% of current cropland area in the United States and Europe, respectively," and that "even this low substitution level cannot be met from existing arable land." Hence, they conclude that "forests and grasslands would need to be cleared to enable production of the energy crops."

Adding insult to injury, the two scientists hastened to add that the required land clearance would result in "the rapid oxidation of carbon stores in the vegetation and soil, creating a large up-front emissions cost that would, in all cases examined, out-weigh the avoided emissions." Furthermore, even *without* the large up-front carbon emissions, they report that individual life-cycle analyses of the conversion of sugar cane, sugar beet, wheat and corn to ethanol, as well as the conversion of rapeseed and woody biomass to diesel, indicate that "forestation of an equivalent area of land would sequester two to nine times more carbon over a 30-year period than the emissions avoided by the use of the biofuel." As a result, they rightly conclude that "the emissions cost of liquid biofuels exceeds that of fossil fuels."

Coming to much the same conclusion in an article in the 27 September 2007 issue of *Nature* was yet another prominent researcher (Laurance, 2007), who discussed the ability of forests to reduce catastrophic flooding. In addition to this important virtue, he wrote that "tropical

forests, in particular, are crucial for combating global warming, because of their high capacity to store carbon and their ability to promote sunlight-reflecting clouds via large-scale evapotranspiration," which led him to conclude that "such features are key reasons why preserving and restoring tropical forests could be a better strategy for mitigating the effects of carbon dioxide than dramatically expanding global biofuel production."

Yet another important reason for not taking the biofuel route was explained by Nobel Prize-Winner Paul Crutzen and three collaborators in a paper published on 1 August 2007 in *Atmospheric Chemistry and Physics Discussions* (Crutzen *et al.*, 2007), where they calculated the amount of nitrous oxide or N<sub>2</sub>O that would be released to the atmosphere as a result of using nitrogen fertilizer to produce the crops used for biofuels. As they describe it, this work revealed that "all past studies have severely underestimated the release rates of N<sub>2</sub>O to the atmosphere, with great potential impact on climate warming." And why would greater N<sub>2</sub>O emission rates have a tendency to cause the climate to warm? Because, as they report, N<sub>2</sub>O "is a 'greenhouse gas' with a 100-year average global warming potential 296 times larger than an equal mass of CO<sub>2</sub>."

The ultimate consequence of this phenomenon -- as best the four researchers could evaluate it -- is, in their words, that "when the extra N<sub>2</sub>O emission from biofuel production is calculated in 'CO<sub>2</sub>-equivalent' global warming terms, and compared with the quasi-cooling effect of 'saving' emissions of CO<sub>2</sub> derived from fossil fuel, the outcome is that the production of commonly used biofuels, such as biodiesel from rapeseed and bioethanol from corn, can contribute as much or more to global warming by N<sub>2</sub>O emissions than cooling by fossil fuel savings." As a result of these observations, Crutzen and his co-workers concluded that "on a globally averaged basis the use of agricultural crops for energy production ... can readily be detrimental for climate due to the accompanying N<sub>2</sub>O emissions."

Thus, in considering the findings of the researchers above, it would seem that growth in biofuel production to combat global warming not only does not do any *good* in this regard, it is actually *counterproductive*. Clearly, such facts must be considered in any attempt to regulate CO<sub>2</sub>.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/b/biofuels.php>.

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