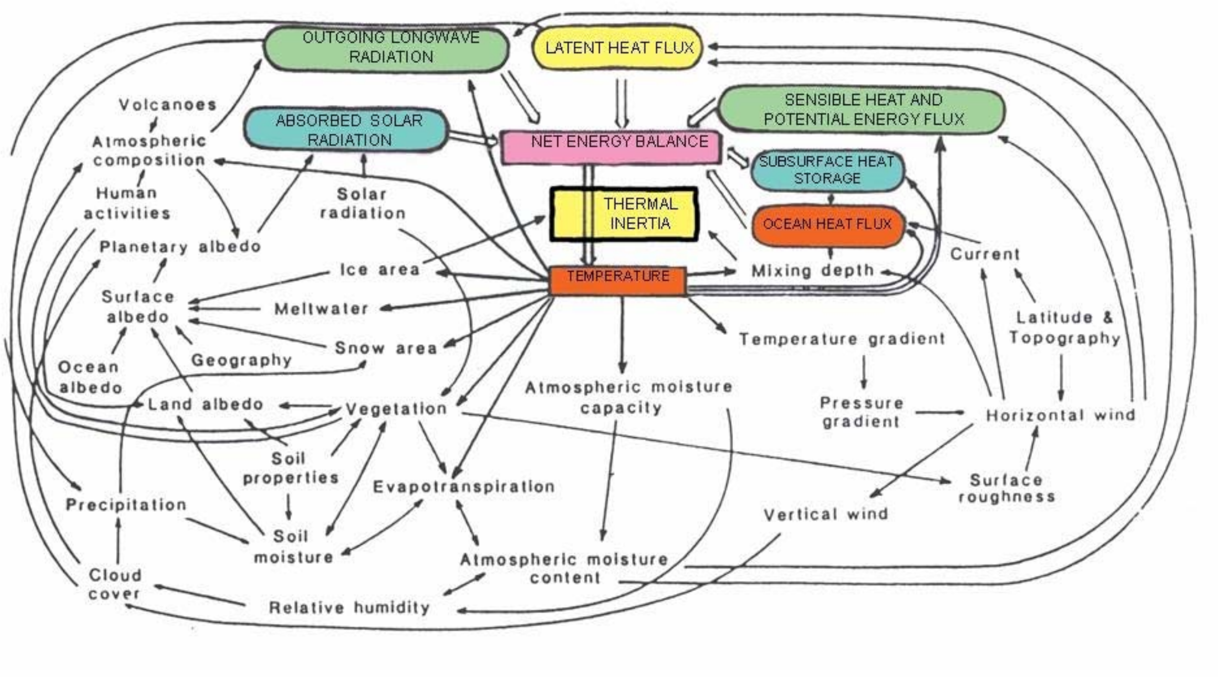
The complexity of Atmospheric and Climate Models: Assumptions and Feedbacks

By Dr. Anthony Lupo, University of Missouri-Columbia

1. Introduction

This is the second article in a series discussing the complexity of atmospheric modeling. If before reading these you felt that atmospheric models should be fairly accurate and/or precise because they are based on well-known physical principles and equations, this author hopes that your faith is somewhat shaken.

While it is true that the physical principles and equations discussed in part one do form the "core" of any atmospheric or climate model, there are processes in the observed system that are difficult to represent due to our incomplete understanding of the process, or the fact that some processes are not exact. Many of these processes are what we call "feedbacks". Feedbacks are manifestations of "non-linearity" in our equations, and this will be described in more detail below (see Fig. 1). Feedbacks also quite often represent the interaction between two parts of the climate system.



Flow diagram for climate modeling, showing feedback loops.
From Robock (1985).

Figure 1. An example of a model schematic (provided by Robock (1985) via Dr. William Gray).

Assumptions are simply based on our incomplete knowledge of the earth-atmosphere system, and thus, a modeler is reduced to representing the process or physics based on his/her best understanding of how the atmosphere works (for example cloud formation). Assumptions can also represent an approximate solution that captures the essence of the system's behavior, but may ignore the nuances (for example, what weather forecasters call quasi-geostrophic theory). Again, these examples will be explained in more detail below, and examples of how they apply to modeling will be given).

2. The Earth – Atmosphere System.

Before we get into too much detail, a primer on what we mean when we refer to the earth-atmosphere system is in order. When studies refer to climate change today, many times they are referring to changes that are occurring across many parts of the climate system. The Earth-atmosphere system itself is composed of four or five main sub-systems[1] (Fig. 2). They are;

1. Atmosphere
2. Oceans
3. cryosphere
4. lithosphere
5. biosphere

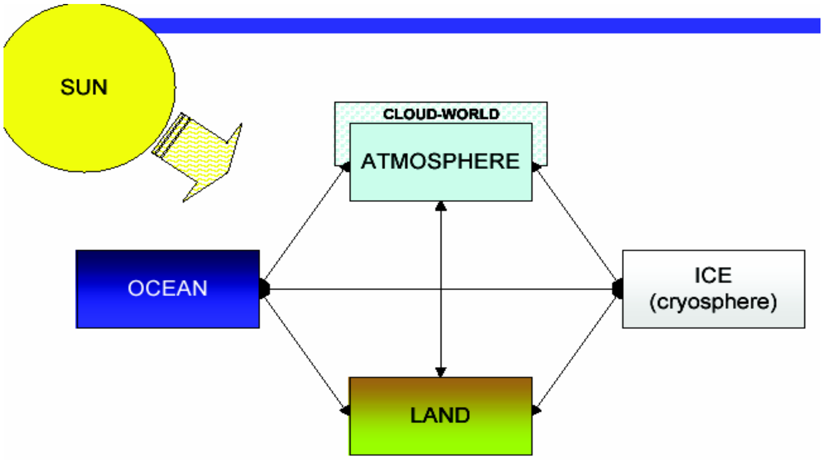


Figure 2. The earth-atmosphere system, courtesy of Dr. Richard Rood.
(http://aoss.engin.umich.edu/class/aoss605/lectures/)

Some scientists consider items four and five as one sub-system. We consider the Earth-Atmosphere system as a "closed system"[1]. This means that we assume mass does not leak out of the system into space, or into the system from space. Energy is exchanged with the solar system around us though. Each sub-system is considered "open", or that both energy and mass are exchanged on a regular basis[1]. The water cycle is a simple example of this concept. Ocean water and ground water can evaporate, eventually form clouds, and then rain back into these sources (Fig. 3). Also, carbon dioxide, one of the major greenhouse gasses, is routinely exchanged between the land and atmosphere, or the atmosphere and oceans.

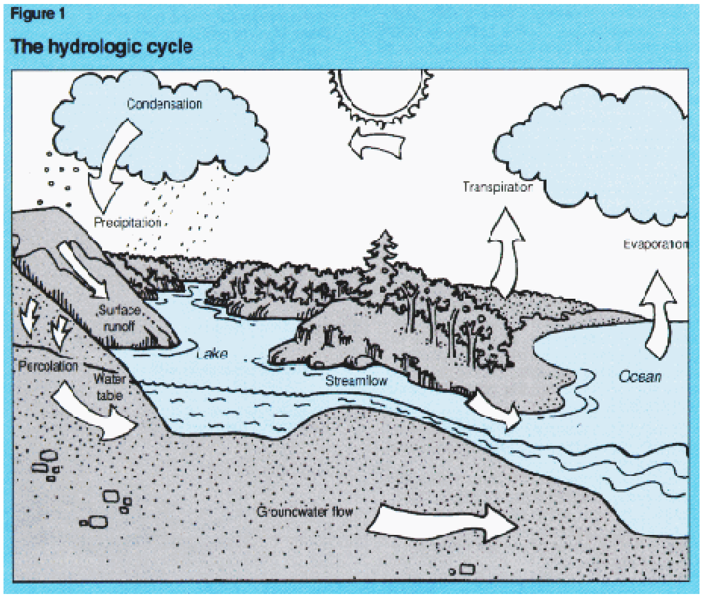


Figure 3. The hydrologic cycle borrowed from:
http://www.und.nodak.edu/instruct/eng/fkarner/pages/cycle.htm

In Fig. 2, the Atmosphere is the part of the system that we consider to be “fast response”, or that it will respond to forces on a time scale of just seconds to a few weeks. The other parts of the climate system are relatively “slow response” and most changes in these components will occur on time scales of a few days to millions of years or more. Climate modeling attempts to represent the atmospheric part of this system. Recall that in the first part of this series, the point was made that climate modeling represented a boundary value problem, or that the atmosphere was essentially a servant to the underlying surface. This point above regarding the time-scale of changes in each component should illuminate why this is the case.

3. *Feedback Processes*

Feedback mechanisms frequently represent very complicated processes. Nature is highly “non-linear”, even though we as human beings attempt to understand nature in a linear way. Feedbacks are a good way to get a handle on these non-linear “coupling” mechanisms. These processes can be thought of as “positive” or “negative” feedbacks.

a. positive feedbacks

A positive feedback is a mechanism by which two variables interact in such a way that a change in one variable causes another to change, and this change acts to further accentuate changes in the first variable. The best way to illustrate this is by example.

It is well known that ice and snow act to reflect more sunlight off a surface than if it were bare. Any skier is aware that sunburn is possible on the slopes, even on the coldest days. A weather forecaster knows that snow covered areas will experience colder temperatures during the day due to snow cover. This works the same way in climate, giving rise to the "ice-albedo" feedback. Albedo is simply the percentage of sunlight reflected off a surface.

If for some reason earth's ice cover increases (decreases), then the planet's albedo will increase (decrease), and in the absence of any other forcings, leading to a cooler (warmer) climate which would further increase (decrease) ice amounts. *This is but a simple example, and like all feedback process models necessarily assumes all other variables in the system will remain unchanged*.

A more complicated example is implicated in the anthropogenic global warming (AGW) problem. Some AGW supporters contend that global warming is not as simple a matter as increases in carbon dioxide leading to increased global temperatures. This more complicated (but far from complete) description involves increased carbon dioxide (A) trapping more heat (B), increasing global temperature (C), and increasing the amount of water vapor (D) in the atmosphere, which traps more heat, further increasing global temperature, and so on and so forth…. The formula in this case might be:

A increases → increasing B → increasing C → increasing D → increasing B → increasing C → etc…

Such a feedback may continue forever unless interrupted by other process. Also, this is the mechanism AGW supporters implicate in the extreme scenarios which predict dramatic temperature rises.

b. negative feedbacks

A negative feedback occurs in such a way that a change in one variable may lead to a change in another variable, which then causes a dampening of the change in the original variable. This feedback is more difficult to understand and better illustrated by example. A negative feedback could be involved in the AGW feedback described above. Let's examine how.

The AGW feedback depends on the fact that more water vapor will automatically increase in the air because temperature increases. Let's assume this is a given. Then, what happens to the water vapor? Does the water vapor become clouds? Will there be more clouds, and what type?

Let's assume that the amount of low cloudiness increases, then the above process becomes;

increased carbon dioxide (A), increasing global temperature (B), increasing the atmospheric water vapor (C), increasing the low cloudiness (D), which then decreases global temperature (B). So, this is;

A increases → increasing B → increasing C → increasing D → decreasing B.

Low cloudiness reflects more sunlight, lowering temperature.

However, the example given here is complex and a negative feedback can alternatively be described far more simply as a change in one variable forcing an opposite change in another. We can describe this easily by using the example of a volcanic eruption. A large eruption will increase atmospheric soot or particulate, reflecting more sunlight, leading to cooler global temperatures. This mechanism produced a notable global cooling after the eruption of Mt. Pinatubo in the Philippines in 1991 (Fig. 4).

Figure 4. A picture of the eruption of Mt. Pinatubo. Enough ash and soot was ejected into the atmosphere to produce a discernable global cooling. Courtesy of (http://www.wikepedia.org)

Note that in the examples of feedbacks given above, there was an exchange in heat and/or mass between one or more parts of the earth atmosphere system. It is these type of processes, positive and negative feedbacks, which are very difficult to quantify and lead us to the necessity of having to estimate and approximate them. Modelers do this in such a way that an atmospheric or climate model will approximate the atmosphere "pretty well", but not represent it perfectly.

4. Assumptions.

Why do we make assumptions in building our models? As shown in section 3, representing feedbacks can be a daunting task indeed. We can only make assumptions about how these processes behave, since they occur at time and space scales that are smaller than our observational network. Some of these physical processes are represented in our equations and can only be included by making assumptions[2]. Let's examine two of the main equations that form the "core" of an atmospheric or climate model. Much of this discussion can also be found in meteorological texts[3]. We'll do this in symbolic form.

a. The First Law of Thermodynamics

The First Law of thermodynamics in the atmosphere is represented as:

Heat added/subtracted = internal energy (temperature) + pressure work.

Simply stated, any heat that is added or subtracted from the atmosphere (an air parcel – or "unit"/"bubble" of air) will be distributed or taken from the air parcel both in terms of its temperature, but also in its pressure or volume. Many processes can change the heat content of the atmosphere, and there is no one way to represent this in an atmospheric or climate model. These include such main players as: 1) the phase change of water in cloud formation, 2) heat coming from the ground or oceans (by conduction or convection), and 3) incoming solar radiation, or outgoing earth (long wave) radiation.

How do we represent these? Notice some of these processes are also part of the feedbacks described in section 3. There are no basic formulas to calculate these, but we can "parameterize" them, based on our knowledge of how these processes behave. In a most crude sense a "parameterization" is a model "fudge factor". Let's take a look at the phase change of water in cloud formation. We know that for cloud formation to happen we need a) sufficient moisture (saturated air), b) instability, and c) upward motion.

In a model, we build computer routines that will assume that the atmosphere will have sufficient condensation nuclei (atmospheric particulates) for moisture to condense on, and then we will build a routine that says;

In the presence of sufficient moisture, and if upward motion is occurring, and the atmosphere is unstable, (bang!) we form a cloud (Fig. 5). A certain amount of heat (X) is released to the atmosphere, and a certain amount of water (Y) is lost to the atmosphere and either forms a cloud and/or rain.

This is a simple explanation of cloud formation schemes. There is no formula, there only are simple calculations, and just a cook-book process based on how we feel the atmosphere behaves. This is the general behavior of these schemes even though there are several variants used in different models. Obviously, given the exact same data set, different cloud schemes will give you different answers for the heat released, clouds formed, and rainfall[4]. Some of these modeling schemes are designed to work better in the mid-latitude weather systems. Others work better in tropical systems.

Figure 5. A picture of a distant thunderstorm (cumulonimbus cloud) looking northwest over Moscow, Russia. This picture was taken by the author in June 2004. The rainbow "spot" in the middle of the photo is a "sundog".

b. The equation of motion

Another type of assumption involves ignoring certain "small" forces and retaining larger ones. In doing this, we lose the generality of the equations, but gain a simpler expression which captures the essence of motion. The equation of motion is represented as:

Acceleration = pressure gradient force + Coriolis force + gravity + friction

In this expression, pressure gradient forces arises from pressure differences in the atmosphere, Coriolis force arises from the turning of the earth (and we could write a paper explaining this!), and the frictional force arises from the contact between the atmosphere and the earth.

The atmosphere has its structure because in the vertical, the pressure gradient force is very large. Gravity is also relatively large, and the other forces very small. Thus, we set vertical pressure gradient force equal to gravity. This is called the hydrostatic assumption, or hydrostatic balance (Fig. 6). Balance represents the concept that one force equals another and the system is unchanging.

How strong is hydrostatic balance? If we looked at the relative size of the two forces retained versus the forces "ignored", the ratio is 10,000:1. Thus, hydrostatic balance (or approximation of the equation of motion in the vertical direction) is a very good assumption indeed! All climate models use this assumption. This assumption also provides the rationale for meteorologists treating the atmosphere as a two dimensional "sheet" on the largest scales.

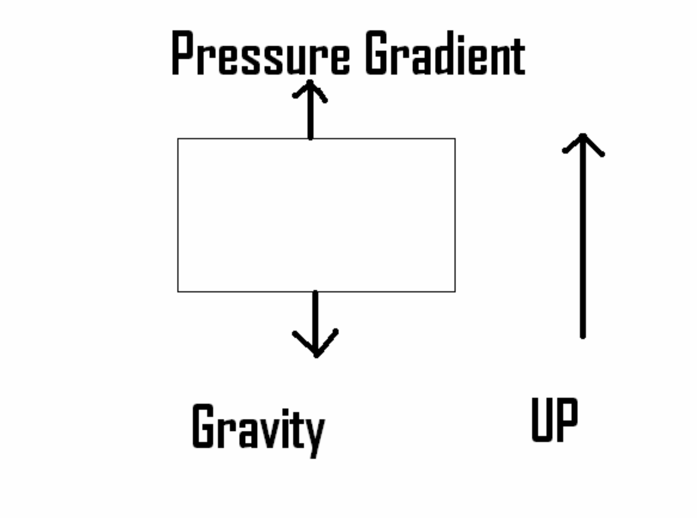


Figure 6. A schematic of the concept of hydrostatic balance in the atmosphere. The square represents a parcel of air. The two forces, gravity and pressure gradient force, are nearly equal.

Another assumption arising from the equation is geostrophic (“earth turning” in Latin) balance (Fig. 7), which, for example, gives rise to the jet streams. In this balance condition, we assume pressure gradient force is balancing Coriolis force in the horizontal direction. This condition is responsible for the winds blowing from the west.

However, this condition is much weaker and the ratio of pressure gradient force and Coriolis force to those processes neglected is only 10:1. This is still a pretty good assumption, and all climate models are based on this assumption. However, this balance condition can be violated quite often and it is necessary for weather forecasters (and weather models) to assume “near” or quasi-geostrophic balance. This involves allowing small motions in the vertical and allowing some three-dimensional structure. As in the hydrostatic balance case, however, we’ve lost some generality in the equations in exchange for simplicity.

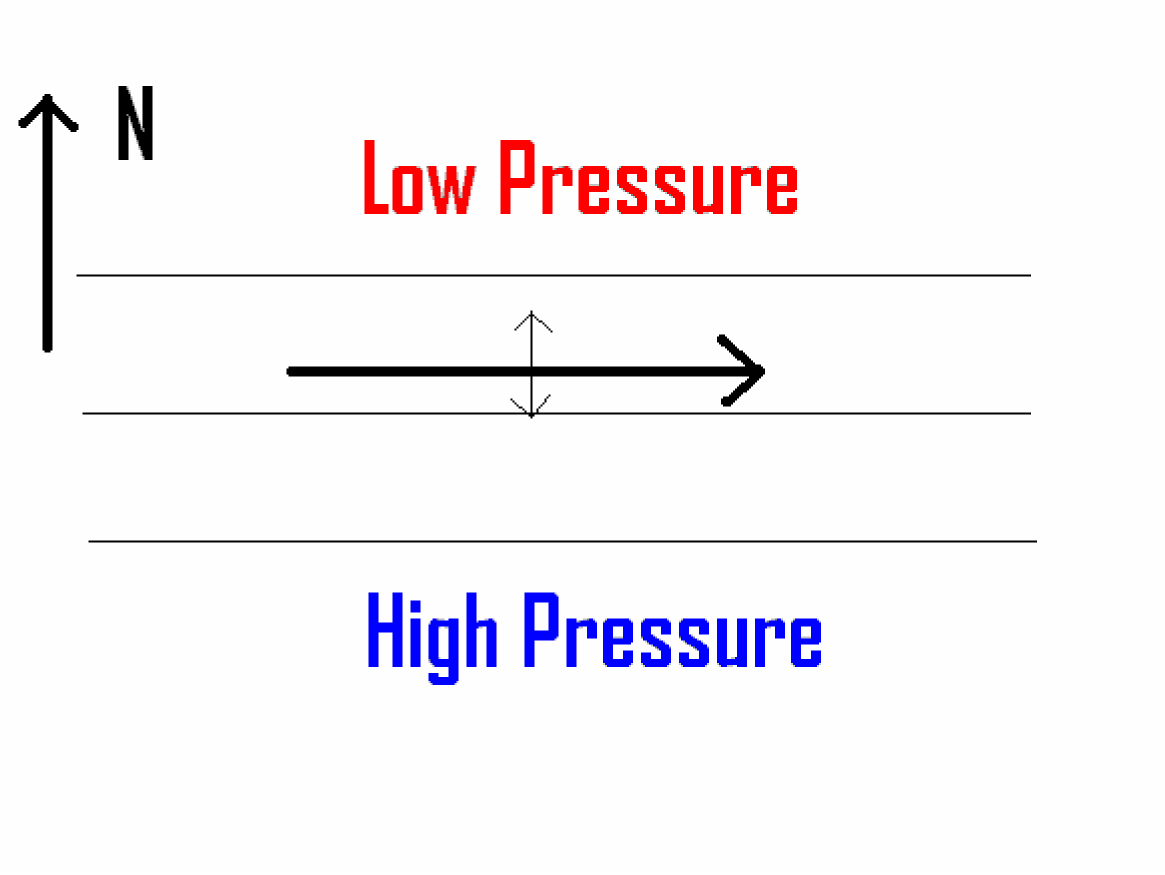


Figure 7. A schematic of the concept of geostrophic balance in the atmosphere. This is drawn to represent the Northern Hemisphere, where high pressure is over the tropics, low pressure over the polar regions. The heavy arrow pointing east represents the jet stream, while the small arrow pointing north (south) represents pressure gradient (Coriolis) force.

5. Summary

In this, the second in a series of papers examining the complexity of atmospheric models, we tackled the issues of feedbacks and assumptions in the models. By now your faith in weather and climate models to predict weather and/or climate far into the future should be very shaky indeed.

The main points to take away from this discussion are that:

(1) the climate system is complicated and made up of numerous interlocking subsystems which interact with each other in ways which we sometimes do not fully understand.
(2) feedbacks, both positive and negative, are processes which arise from non-linear forcing in the climate system, within a sub-system or occurring at the boundaries (interactions) of each subsystem. They too can play a key role in the results of the model. In some cases, there is uncertainty about whether changes would bring a positive or negative feedback or none at all

(3) making assumptions in climate modeling is a necessary evil. Assumptions can provide us with a simpler representation of the model physics at the slight cost of some generality, or these assumptions can represent our best understanding of a certain atmospheric process. The wrong assumption of course can lead to an incorrect model result if the process is of significance

References:

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