The complexity of Atmospheric Modeling

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1. Introduction

It's been said many times by those who've built computer models that putting these together are like making sausages, they can be quite good (when they work) but you don't necessarily want to know what goes into them. This is not to make light of computer modeling as they are the best tools we have to analyze and study the climate system. Nonetheless, atmospheric models can be fairly complex (Fig. 1), and their output should be examined carefully and cautiously.

We also use computer models to guide our weather forecasts in the short term (several hours to a week) and long range (months to seasons). The most controversial use of the models is to attempt to determine what the future climate may look like by 2050, 2100, or beyond. It is often stated that; "if we can't forecast the weather two days out, how can we forecast what will be occurring in 2100"? The (inconvenient) truth is that we cannot, but there are strategies we can employ to credibly examine what may happen at that time. There will be more about how we go about it below.

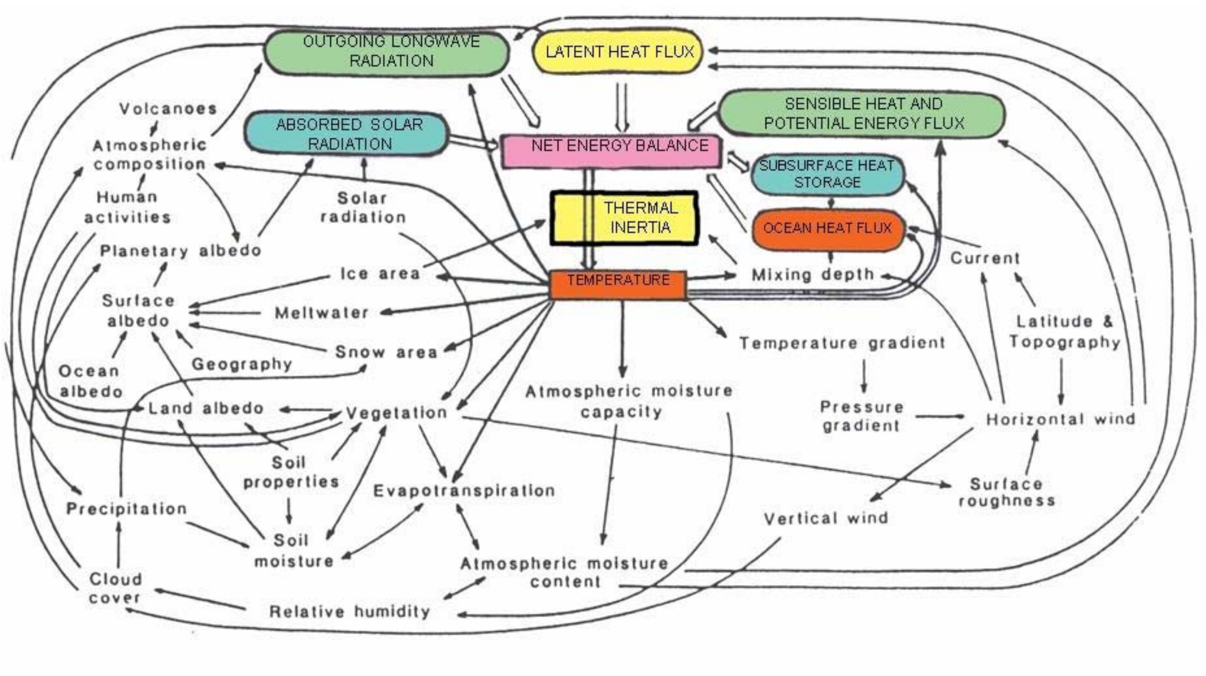
In order to get started, we need to define what an atmospheric model is and is not. To do this, I'll invoke the "scientific method", which is a procedure that should guide good and credible scientific investigation. The method is at least as old as Sir Isaac Newton, and possibly even before him. The steps for the scientific method [1]:

1. Identify the issue or problem
2. Investigation
3. Data collection
4. Form Hypothesis
5. Test Hypothesis
6. Accept or Reject hypothesis based on the conclusions of experimentation
7. If we reject the hypothesis, return to step 2
8. If we accept the hypothesis, move on to the next problem (or solution).

Thus, a model is simply a tool through which we accomplish this process. *In fact, a model itself is simply a hypothesis*. This is not my own original thought, so in order to avoid being guilty of plagiarism, I'll state that up front. (I can't recall offhand where I found this thought).

The definition of an atmospheric (climate) model is;

An hypothesis [frequently in the form of mathematical statements] that describes some process or processes that we think are physically important for the workings of the atmosphere (climate and/or climatic change) that has physical consistency in the model formulation and the agreement w/ observations serving to 'test' the hypothesis [i.e., the model]. The model [math] should be shortened [approximated] for testing the hypothesis, and the model should "jive" with reality.



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).

This means that any atmospheric or climate model is simply a "box" that represents how we think the atmosphere or climate works. It's our best guess or approximation. These models can be as good and as simple as the model creator makes it. A colleague of mine would stress the point by saying that a particular atmospheric model is "planet (name of model here)", and not quite Earth's atmosphere.

I like to illustrate this by analogy and showing a stick figure cat. This is my best artistic representation of this animal, but it looks nothing like an actual cat. You may be a good artist, but you cannot draw (create) any cat that would be as pleasing to the senses as the real thing (Fig. 2).

2. Model basics and problems

An atmospheric model itself is composed of seven basic mathematical equations representing seven basic variables which describe the instantaneous state of the atmosphere. This represents a solvable set of equations which can describe all atmospheric motions / processes. The equations represent three (four) basic physical principles, and all correct theories and models representing atmospheric motions will not violate these basic principles:

1. conservation of mass (dry mass and water mass)
2. conservation of energy
3. conservation of momentum

However, within these equations are processes for which we have no precise formulation for, and some observations (and their long term changes) that we do not know precisely. Examples of these processes are cloud formation, heat exchange between the earth's surface and the atmosphere, and measurement and change in solar radiation. These are processes which must be represented by "parameterizations", "constants", or "fudge factors". In other words, there are processes that we still don't understand. This is but one of the problems with models and part of their complexities. In fact, more computer programming in devoted to these kind of processes rather than the basic equations referred to above. I'll discuss these physical processes and feedbacks (e.g., Fig. 1) in a follow up document.

Figure 2. An analogy for the relationship between a model of the earth's atmosphere and the observed atmosphere. The cartoon image is courtesy of (www.comedyzone.net), and the kitten from (www.gotopetsonline.com).

There are other problems with the models that manifest themselves as "error", which causes a "forecast" to go hopelessly awry after some time. You can read about these topics in any textbook on the subject of modeling [2],[3]. One has to do with the data that we feed these models. There just is not enough of it. Weather forecasts are made with data that is measured twice a day in the USA, but once a day in most other locations, and the highest density of this information is garnered over land. Thus, there are vast areas of the atmosphere not even represented.

Combine this with an instrument's inability to measure, for example, temperature with infinite precision. There is always some degree of measurement error based on the precision of the instrument. Thus, there will always be some uncertainty in measurements themselves (Heisenberg's Uncertainty Principle). This uncertainty will be manifest as error, and can be measured by using basic equations or estimated by running on model parallel with another except you make slight adjustments to the initial data the model is fed. This type of error can render a model's prediction as garbage as quickly as four days [4]!

There is also some difficulty in representing the mathematical processes themselves in the basic equations. These processes themselves can only be "approximated" using an infinite series. If you've taken calculus, you may recognize the Taylor or Mac Lauren series. These are "truncated" in order to provide an estimate for a certain quantity. This is how a calculator gives you a result for the $\sin(40^{o})$, for example.

These numerical methods are used to solve the equations, and as I tell my students in my Numerical Methods in the Atmospheric Sciences class, modeling is a game of choosing the right tool for the job. One would not use a 10 lb sledge to drive a nail into the wall to hold up a picture when a small hammer would do. Conversely, you cannot use the small mallet to break large rock formations. So it is with numerical methods.

Given the paucity of observations and the problems with the fundamental math, there is one more problem that arises and that's the problem of model resolution. It is not possible to represent atmospheric processes, such as thunderstorms, occurring on space scales smaller than the observations themselves. The energy, for example, from these smaller scales can be falsely represented on the larger scales.

All of these issues must be balanced with the amount of data a computer can crunch and how long it takes to produce a model simulation. Thus, I hope that this discussion about computer models has introduced a lot of skepticism into the reader even when looking at a weather forecast. To summarize, the problems which introduce error into atmospheric models are:

1. lack of knowledge of some basic physics
2. error in numerical methods chosen (and which)
3. precision of the observational measurements
4. amount of data available (in time and space)

3. *Modelling strategies, Weather Forecasting versus Climate Modelling*

a. Weather forecasting

Most people are familiar with weather models as they are discussed by their favorite television weather forecaster, either locally, or on the Weather Channel. Weather forecasting in principle is what we refer to as an "initial value problem". That is, we need to gather observational data, which is then quality controlled. This is no small problem because data is gathered from several sources and the data needs to be checked for consistency with other data, and with some of our basic assumptions about atmospheric structure and behavior. The data at this point are distributed into a grid or grid-like arrangement.

Then forecasts can be created from this “initial field” of data (Fig.3), and along the way the data need to be messaged constantly in order to keep error from growing too rapidly. Forecasts can then be produced for the weather forecaster in order to provide guidance as they generate a product for the public (Fig. 4). For how long one can forecast outward in time, is ultimately dictated by the size and rotation rate of the planet. Using Earth’s dimensions, forecastability as an initial value problem is on the order of 10 – 20 days. This is what we sometimes refer to as the forecasting “wall”. Thus, we will not in my lifetime be able to use dynamic model predictions to forecast the weather well beyond this time period. Clearly, another strategy is needed to make long range and climate forecasts.

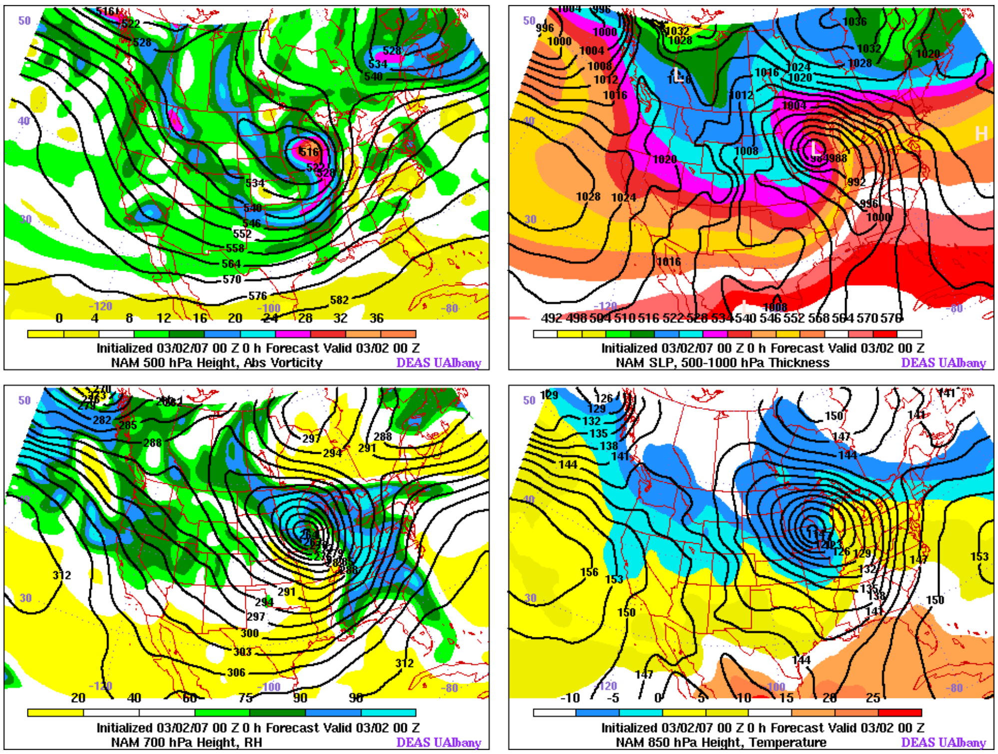


Figure 3. Initial fields of a weather forecast model generated from 7:00 pm, 2 March, 2007 (courtesy of the Department of Atmospheric Science at the State University of New York at Albany)

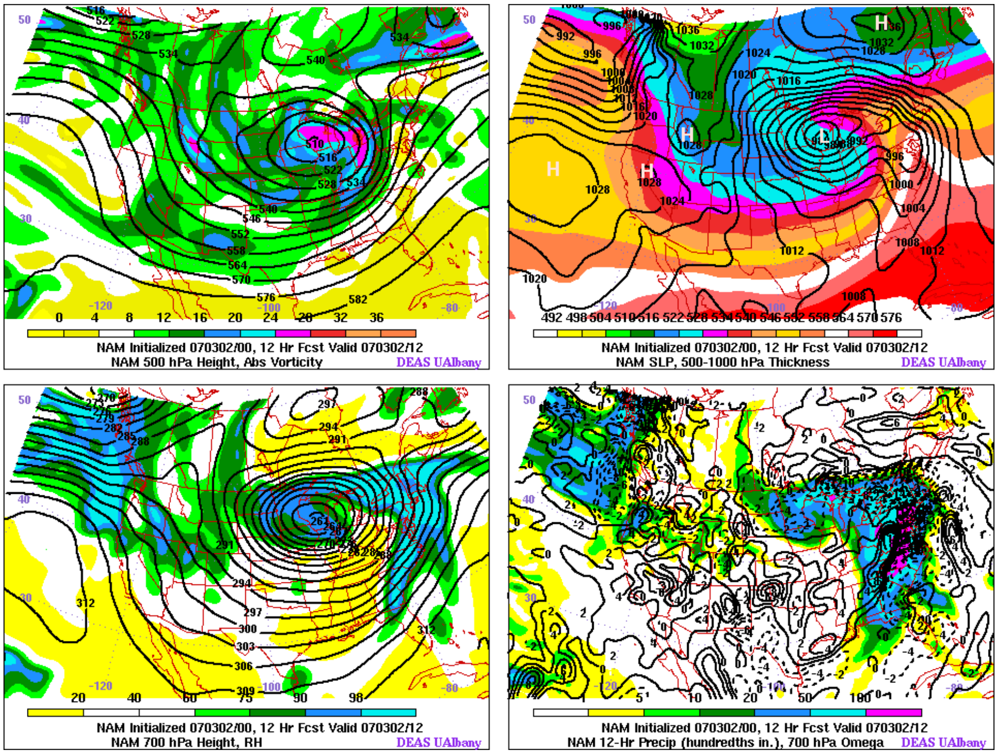


Figure 4. A 12-hour forecast based on the data shown in Fig. 3.

b. Climate modelling

Climate modeling, on the other hand, employs a different strategy. Climate modeling of the atmosphere in principle is what we call a “boundary value problem”. This is because the atmosphere responds very quickly (relatively speaking) to changes in the underlying surface. Changes in the underlying surface, that is the land surfaces and ocean surfaces, occur very slowly. Thus, the atmospheric climate we are familiar with is a servant to the underlying surface. To complicate matters, we are still not completely sure about how exchange between the atmosphere and ocean (and land) take place.

There are two distinct types of climate models;

1. Diagnostic, or equilibrium models (ECM). These represent a “steady state” or “unchanging” processes with time. The ECM is most commonly solved for climatic means and variations.

2. Prognostic models, where changes in variables with time are crucial. The time variation of particular variables are the desired output (i.e., a time series). Thus we can calculate changes in climatic means and variances.

Both are employed in the study of climate, and, generally, the diagnostic model is simpler and produces output faster. Weather models are prognostic models and definitely more complex, but we can use them "forecast" climate.

Modelling in general, especially climate modeling, generally follows one of two strategies; either a deductive approach or an inductive approach.

The inductive approach: employs *a priori* reasoning, because beforehand, we know what processes are important to the problem we are studying and we construct the model around these processes.

The deductive approach: employs *a posteriori* reasoning, because after the fact, we calculate all the processes thought to be important and then figure out what processes are the most important (largest).

Thus, how is it that forecasts for 2100 are made? One way of doing this is to start with today's conditions in a "souped-up" weather forecast model, and slowly add carbon dioxide to simulate the rise in greenhouse gasses and then see what the model produces. This concept would be ideal, except that there are several atmosphere – ocean interaction processes that act on multi-year to multi-decadal time scales that we have not mastered when attempting to model past climate. Examples of these phenomena are ENSO (El Nino and La Nina), the Arctic Oscillation (AO)/North Atlantic Oscillation (NAO) and on longer time scales the Pacific Decadal Oscillation (PDO) or Atlantic Multidecadal Oscillation (AMO). We don't completely understand the physical workings of these processes yet, thus, it is not surprising that we cannot model them. Again, this is only one of the problems we must overcome.

In order to test whether or not we can rely on this methodology, we can attempt to model the Earth's climate since, say 1850, and get today's climate correct. It is not possible to do this without constant adjustments to the model. This is why model simulations of future climate show monotonic increases in global temperature over the next 100 years, rather than something that looks like observations from 1850 – 2000 which featured two periods of temperature rise, bookending two periods of fall.

The other strategy is to first allow the climate model to "equilibrate" or find a steady climate under conditions we think will exist, and then look at 30 years worth or more of data in order to determine what the climate of this future time will look. This model simulation is compared to a "control" run of the model (present day conditions). This strategy has been used in my research group [5] in order to examine how increases in carbon dioxide and a warmer climate might influence the strength and character of the jet stream. This strategy is perhaps a better way to examine the problem given today's understanding and technology.

c. Model based projections of increased temperature.

So what about these temperature projections that state that the possible rise in global temperature by 2100 may be as much as 1° C to 6° C (1.8° F to 10.8° F) (e.g., see Fig. 5 and [6])? These projections are based on a strategy by where a model is run from the same initial conditions, or slightly altered initial conditions many, many times [7] [8]. This is called a model ensemble.

Generally, due to many of the same problems discussed in section two here, and the nature of the basic equations used in the model, a large range in global temperatures is a natural result in creating an ensemble. The more times you run the model and the longer the time period used, the greater the spread in the predicted variable, here global temperature. This is a concept we refer to as *"sensitivity to the initial conditions"* (SDIC), and such behavior is inherent in, such as earth's climate system, that display chaotic characteristics. Chaos theory another name for the study of non-linear dynamics, which are represented by unsimplified forms of the basic equations referred to in section two.

Still, the upper end of the range in global temperature increases cited above can be quite frightening to think about! Do we really have to worry about these? Many times, those proponents of global warming will show the more extreme scenarios in the upper part of the range. They do this, as even many times they will concede to move people into action.

Even if we concede the point that the current climate change is driven by humans, and we were to believe that the models are reliable, the odds are with us. Most of the model runs that are used to create the temperature ranges tend to cluster at the lower end of the range (1.0° C – 3° C or 1.8° F – 5.4° F). At the lower end of this range, this is a slightly greater warming over the next century than has occurred over the last 100 – 120 years. This is a warming we can adapt to.

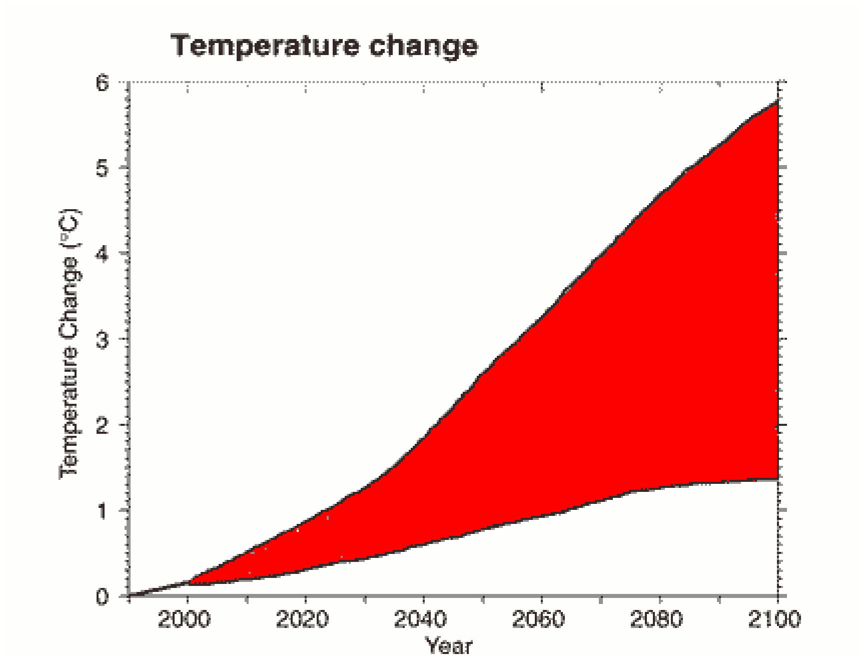


Figure 5. Global temperature changes projected for 2100. The figure was borrowed from the Intergovernmental Panel on Climate Change, Third Assessment Report.

4. Some final thoughts

It is hoped that the reader will look with skepticism on the climate model "forecasts" cited by and discussed by the those proponents (and even opponents) of human induced global warming. In this document, we have barely scratched the surface in discussing the complexity and problems with computer models. We will follow up this document with further discussion of the physical processes that we don't understand, or whose impact on the outcome in a climate model is difficult to predict. We will also discuss advances in understanding these processes [9]. We will also discuss why it is not correct to believe that a warmer climate will lead to a wilder climate.

In summary, we've stated here that models represent our best understanding of how the climate works at the present time. We showed the basic physical reasoning that forms the basis of any numerical model as well as discussing modeling strategies used. Finally, a brief discussion of the principles behind the construction of the projected temperature increases, and how these are typically mis-reported in order to exaggerate are discussed. Finally, those who would argue for disastrous climate change and hang their hat on the output of climate models have a weak case indeed.

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