From Airplanes to Climate Change

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The development of a new type of airliner is way too expensive for guesswork. Before the first real plane is built, the engineers *know* how much thrust the engines will produce, how much the plane will weigh, how fast it will be able fly at various altitudes, how much fuel will be needed to travel from Denver to Dallas, how the plane will respond to a pilot's commands, and how much it will cost to manufacture. They have to know these things, because they are betting the company on the success of the design, and because you and I (and the engineers' mothers) will be riding on the plane.

So how do they know?

The answer is arithmetic. Lots of arithmetic. The engineers can simulate the airliner before it is built, using what is called a "mathematical model." The "mathematical" models are based on physical ideas developed by Isaac Newton and other scientists. The math is just a language that can be used to express those ideas, in the same way that English can be used to express ideas about history or art. The models work very well.

The modern world is full of mathematical models. They are used to design skyscrapers, bridges, cars, and space ships. They are used to search for oil, to forecast the weather, and to predict where and when rivers will flood when snow melts in the spring. And they are used to predict how the climate will change between now and the end of this century.

A climate model has a lot in common with the models used to simulate airplanes. Fluid dynamics and thermodynamics are front and center in both. Even the mathematical methods used are very similar. When a climate model simulates the winds, or when an airplane model simulates how the air moves past a wing, the underlying principles are Newton's laws of motion, which say that a particle of air moves in a straight line at constant speed unless acted upon by a force. When a climate model simulates the change from winter to summer, or when an airplane model simulates the temperature inside a jet engine, the underlying principle is that the temperature of the air increases when heat is added.

To measure the climate of the real world, we average together measurements accumulated over a long period of time, usually thirty years or more. The measurements come from weather stations, balloons, radars, satellites, airplanes, and buoys floating in the oceans. They represent a record of the weather, hour by hour, all over the world. A picture of the climate is built up by calculating long-term averages and other statistics from the hour-by-hour weather data.

Climate models work in much the same way. They simulate the hour-by-hour weather, all over the world. When a climate model is used to predict how the climate will change by the year 2100, it "marches" forward in time, taking time step after time step, starting from today's weather. Each time step is just a few minutes long. It takes a lot of time steps to simulate a century. As the model marches along, the sun rises and sets, storms grow and decay, and the seasons change, all in the simulated world.

Many things affect the climate. In addition to the forces that affect the winds, an atmosphere model includes the effects of visible and infrared radiation, cloud formation, and small-scale turbulence. The simulated climate is determined by averaging the simulated weather. In fact, the models used to simulate climate are very similar to the models used to forecast the weather.

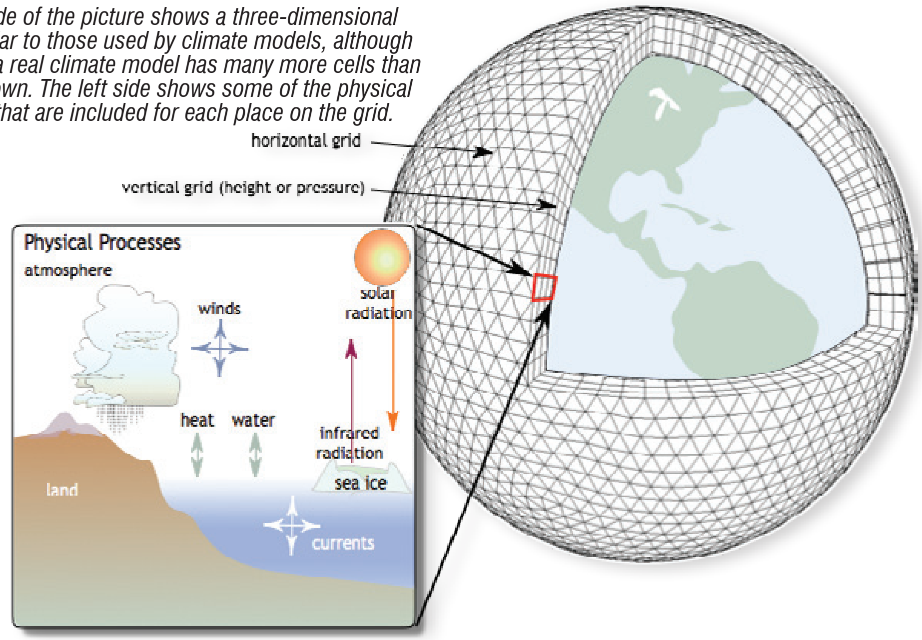
Both weather and climate models include sub-models of the land surface, as well as the atmosphere. Land surface models predict the temperature and moisture content of the soil. They are needed for weather forecasting because the ground warms and cools quickly during the day-night cycle, and this has a strong effect on the air temperature and weather systems such as thunderstorms.

Climate models have to include more components than weather models. They predict the ocean's temperature, salinity, and currents, from the sea surface right down to the bottom. The ocean can hold tremendous amounts of heat, which the ocean currents carry from the warm tropics towards the poles. The formation and melting of sea ice are also included. The newest models also predict the chemical composition of the air, the greenness of the trees and grass, and changes in the polar ice sheets. The figure at right gives an idea of how this all fits together.

Climate models include less spatial detail than forecast models, because this allows them to simulate a year as quickly as forecast models can simulate ten days. Today, a state-of-the-art climate model represents the area of the Earth with about 50,000 points. That works out to about 10,000 square kilometers per point, a little bigger than the area of Larimer County in Colorado. The vertical structure of the atmosphere is represented with about 50 layers or "shells," extending from the surface into the stratosphere, for each of the 50,000 points. The ocean is represented with about 50 layers. As computers get faster, the spatial detail of the models can be increased. Both weather and climate models need the fastest computers in the world.

Tomorrow's weather is usually predicted with good accuracy, but we all know from experience that the forecasts go bad beyond a few days. How then can a climate model predict what is going to happen in a hundred years? The answer is that weather and climate forecasting are very different kinds of prediction. Here's an example: I'm writing these words on June 8th, in Fort Collins, Colorado. Starting from today, no one (and no model) can make a skillful weather forecast for December 8th of this year. Nevertheless, I can predict, with high confidence, that next December 8th in Fort Collins will be colder than today, because I know that the average weather here in December is colder than the average weather in June. A climate model can predict that too. It's kind of a no-brainer.

The right side of the picture shows a three-dimensional "grid" similar to those used by climate models, although the grid of a real climate model has many more cells than the one shown. The left side shows some of the physical processes that are included for each place on the grid.



Ask yourself, *why is it possible* to predict the seasonal change from June to December, even though we can't predict the weather that far out? Why is the average weather in Fort Collins different between June and December? You probably know that seasonal changes in the average weather are due to the seasonally changing position of the Sun in the sky, which is caused by the movement of the Earth in its orbit around the Sun. The movement of the Earth in its orbit is a time-dependent "forcing." Barring some fantastic catastrophe, the Earth will keep moving around the Sun, just like it did last year. Naturally, climate models have been designed to take that into account, and as a result, they can easily simulate the observed seasonal changes of the average weather.

In contrast, day-to-day changes in the weather are *not* due to changes in forcing, because the forcing hardly changes from one day to the next. The day-to-day changes in the weather arise from the chaotic movements of individual weather systems, which can't be skillfully predicted beyond a few days.

Predicting climate change is something like predicting seasonal change, because both occur in response to changes in forcing. For example, what would happen if the Sun went dark, or if a giant asteroid hit the Earth? Answer: The climate would change in a hurry. Is such a climatic response predictable? You bet it is. Less dramatically, the climate can also change in response to large volcanic eruptions, changes in the shape of the Earth's orbit, or changes in the composition of the atmosphere. These are all examples of time-dependent "forcings." If changes in the forcing can be predicted in advance, then the response of the climate system can also be predicted. That's why it's possible to predict climate change, even though weather forecasts go bad after a few days.

The models that are used to design airplanes have been developed over a period of decades, and are tested by comparing their predictions with measurements. They are not perfect, but their limitations are well known, and they are getting better year by year.

Climate models were first developed in the 1960s and are currently being improved at a couple dozen centers around the world, including several in the U.S. They are tested, in part, at the component level. For example, the components that represent cloud processes are tested by comparison with specially collected, highly detailed measurements of clouds. The models are also tested as complete systems, through weather forecasting, simulations of the present climate, and simulations of past climates such as ice ages. The models are not perfect, but their limitations are well documented. Improvements are made every year through the work of the world-wide climate research community, and also by taking advantage of the increasing power of computers. Within the next ten years, faster computers may make it possible to run climate models with 50 million points, instead of the 50 thousand that we use today. Each of the 50 million points will represent an area about the size of the combined Fort Collins campuses of Colorado State University.

If you are interested in learning more about climate models, especially their history, you might want to take a look at this recently released book, which is aimed at a fairly general audience:

Donner, L., W. H. Schubert, and R. C. J. Somerville, Eds., 2011: *The Development of Atmospheric General Circulation Models: Complexity, Synthesis, and Computation*. Cambridge University Press, 272 pp.