What Is a Climate Model Anyway?

Camden Opfer

Abstract

Oftentimes the public discourse around climate change comes down to which authority someone chooses to put their trust behind. This may be a well-liked politician, a family member who is trusted to stay up to date on the news, a religious leader, or the scientific community. It is difficult to say which of these is the "correct" way to gain an understanding of climate change, but oftentimes the benefits of trusting science are hidden by technical, inaccessible communication about scientific methods. As a small part of resolving this issue and providing transparency to scientific approaches, this article includes plain language explanations of what climate models are, how they work, what questions they can and cannot answer, and what uncertainties remain in climate predictions.

Introduction

Throughout human history, being able to predict weather and climate has been a useful tool. Whether to avoid an approaching storm, choose a crop well-suited for the drought or flood conditions of a given year, or assessing the health of ecosystems, the financial and social benefits of accurate weather and climate modeling are large. As a result, climate research has been an active field for centuries. As far back as the 1850s, several scientists identified that carbon dioxide (CO_2) and other gases in the atmosphere could retain heat through what we now call the greenhouse effect (Dominelli 2024). This was carried out not by modeling particular weather events and conditions, but considering the bulk, global amounts of heat being transferred between the Earth and its atmosphere, as shown in figure 1.

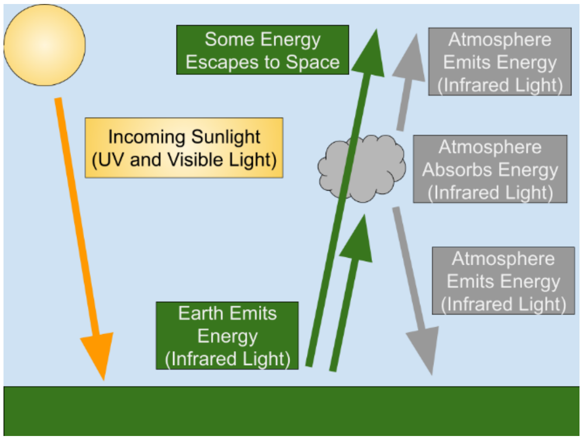

Figure 1: A schematic showing the bulk processes understood by climate science in the 1850s. Sunlight warms the Earth, which then emits energy (infrared radiation). Some of this energy is absorbed by the atmosphere, and the warmer atmosphere emits more energy towards the Earth.

Today, climate modeling is much more advanced, predicting the conditions at thousands of points around the world at various altitudes and depths (Edwards 2011). This approach allows for a fuller understanding of how individual processes like the location of the jet stream or the melting of Arctic sea ice will interact with climate change. This detail provides more certainty around climate projections than ever before, but the complex computational systems needed to accomplish this are much more difficult to explain and understand.

To address this outstanding issue, this paper outlines the basic principles and structures used by climate models, then it ties the form of these models to their function—what they are able to accurately predict and what uncertainties remain.

Model Infrastructure

Modern climate models are all run on computers—often supercomputers—which dictates most of what can and cannot be accounted for. Computers are very efficient at performing arithmetic for matrices (grids of numbers), but they require quite rigid structures and algorithms that make some processes harder to account for. As a result, climate models rely on a grid of locations around the world and at several altitudes in the atmosphere, each of which is assigned values for temperature, humidity, and many other variables. In reality, all of these variables vary over quite short distances, so it is desirable that, in models, the distance between grid cells is as small as possible. Figure 2 illustrates how the improvement of computers over just three decades from 1990 to 2007 allowed for much finer resolution in what climate models account for.

Despite these continuous improvements, there will always be processes which occur at a scale smaller than the climate model resolution. For example, when a cloud forms, it starts as a few droplets, then grows to potentially span several miles, but often not an entire model grid cell. This is termed a "sub-grid scale" process since it happens at a spatial resolution smaller than the grid box of a climate model, and it cannot be directly modeled. Many such processes exist, and improving how they are incorporated into models is a key area of active research, as will be discussed below.

In order to generate grids of conditions tens or hundreds of years in the future, climate models must then progress the weather forward in small chunks of time called timesteps. For the National Center for Atmospheric Research (NCAR) Community Earth System Model (CESM), the current model version runs at an atmospheric timestep of 30 minutes (Danabasoglu et al. 2020). This means that the atmospheric conditions in each cell are calculated at 30-minute intervals, with each model state relying on the last.

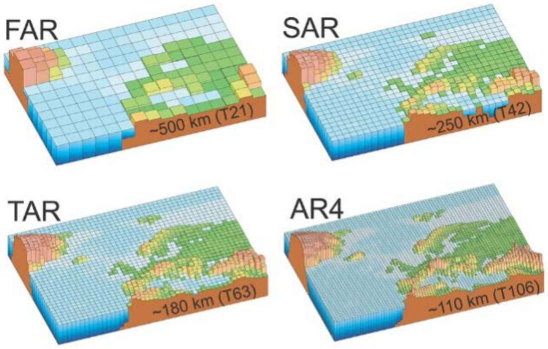

Figure 2: A demonstration of the improvement in figure size between the first four IPCC Assessment Reports. First Assessment Report (FAR, 1990), Second Assessment Report (SAR, 1997), Third Assessment Report (TAR, 2001), and Assessment Report 4 (AR4, 2007) model grids are visualized over Europe. Image Credit: IPCC AR4, Figure 1.4

To calculate the changes in temperature, humidity, and other variables from one timestep to the next, known principles and equations from physics are applied. For example, when one location has higher pressure than another, it has more air "piled up" above it. As a cornerstone of fluid dynamics, it is well known that gravity will mash this extra "pile" of air down, and lead to a flow of air from high to low pressure. This is termed the pressure gradient force, and it is one of many forces which result in changing conditions both in reality and in a modeled climate.

Since a massive variety of processes happen within the atmosphere and interact with it, not all of them are large enough in magnitude to impact forecast results. However, as models have continued to improve, an increasing number of these processes can be accounted for. Figure 3 demonstrates this

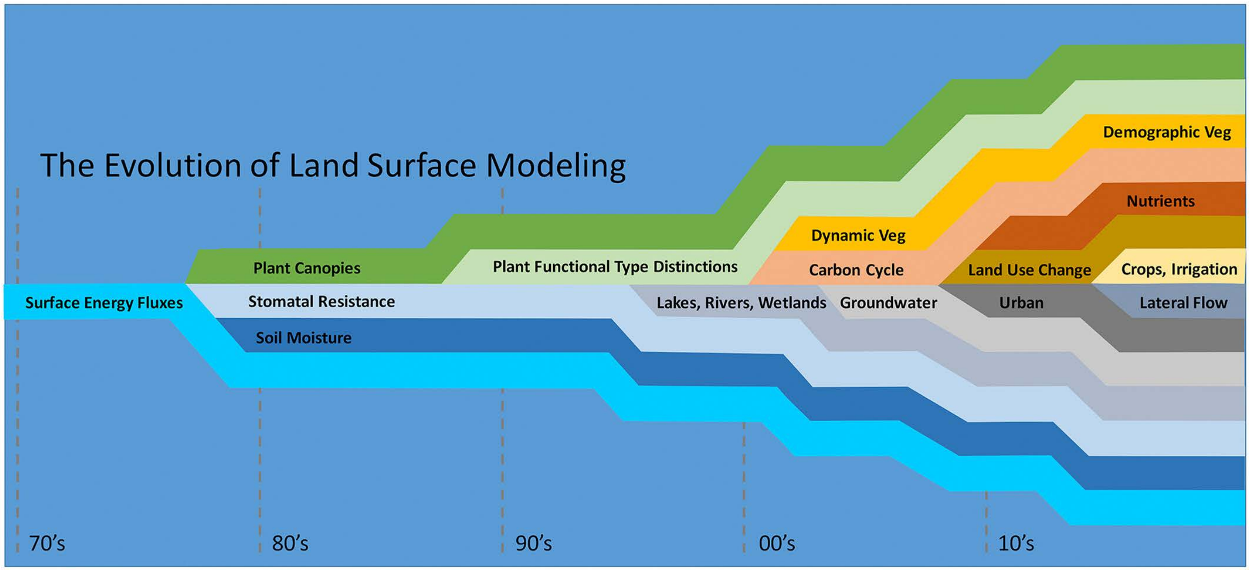

Figure 3: An illustration of how an increasing number of processes are accounted for by climate models. This figure focuses on the land surface component of climate models, but similar improvements have been made in the modeling of atmosphere, ocean, and other processes. Image Credit: Fisher and Koven 2020.

buildup of model quality over the last five decades for just the modeling of land surfaces— which is paralleled by the many improvements made in that time in modeling oceans, atmosphere, sea ice, and more.

To check the validity of the physics being used, climate models are often compared against historical observations, verifying that the progression of the model is within an acceptable range of what is known to have happened.

Sources of Uncertainty

As anyone who has checked the forecast for a winter storm in Colorado can attest, weather models often have large uncertainties, and potential errors, associated with their predictions. So how can climate predictions—which span much further out into the future—have enough accuracy to be useful?

The simple answer lies in what they predict. While weather forecasts include exact conditions at a particular location and time, climate predictions are used to estimate average conditions. This can include averaging over space, for example, finding the global mean temperature, or time, like finding how often an El Niño event happens. By taking these averages, potential errors are smoothed out, leaving much more certainty in the resulting values than the individual forecasts.

Though this approach allows climate models to be quite helpful, uncertainty remains in some predictions. This is the target of continuous research carried out by model developers.

Model Physics

The most obvious source of uncertainty in climate predictions is how well the relevant physics are understood and implemented into code. For the most part, processes ranging from wind formation to evaporation of ocean water to warming of the surface from sunlight are well understood, and they have a set of well-established equations that govern them. However, climate models are limited to the computational resources available, which requires climate scientists to carefully balance the resolution of the model's grid with the length of a timestep and how many processes are accounted for.

When a process can't be incorporated in this way, a "parameterization" is often used. This is an equation or assumption or physical simplification which makes predictions more feasible, but also means that the model is not fully capturing the state-of-the-art physics known within the field. For example, as stated earlier, it can be difficult to predict snowfall events in Colorado, especially because they involve sub-grid processes. Rather than directly estimate where the storm clouds will be and how much snow each backyard will receive, one practical parameterization would take temperature and humidity values of each grid cell, and then estimate the percentage of that cell which will be covered in clouds, and what volume of water contained in those clouds (if any) will fall as snow.

Overall, the physics used by climate models maximizes the available computer power, but is unable to capture every process perfectly, leading to one key source of error.

Internal Climate Variability

Another reason why climate forecasts don't represent exact weather conditions years into the future is the way that the climate quickly diverges into very different future scenarios even when changes to the starting conditions are microscopic. This is shown in figure 4, where changes on the order of 10^{-14} °C were made to the 1920 temperature values of 40 separate climate models (called an ensemble), which quickly fanned out to provide high and low estimates of global average temperature seen as the gray shaded area (Kay et al. 2015).

This is a manifestation of the butterfly effect where, as the saying goes, "Something as small as the flutter of a butterfly's wing can cause a typhoon halfway around the world." Even a tiny change in conditions can have a massive impact on what is predicted only a week or two later. This can be seen as a problem with climate prediction; it is unreasonable to expect any climate model to have such perfect knowledge of conditions today that it can perfectly identify what will happen in the future. On the other hand, by understanding this uncertainty, more context and nuance is added to the results.

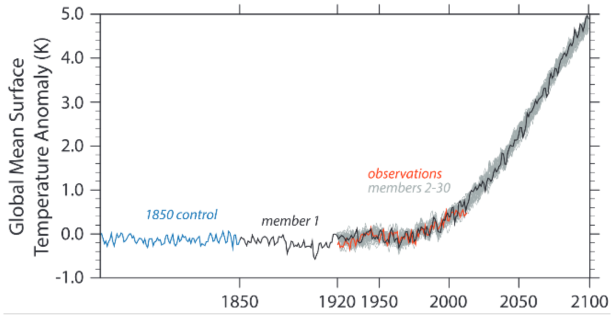

Figure 4: A plot of predicted global average surface temperature from NCAR's CESM large ensemble. In blue, the model is run with constant greenhouse gases, then the true impact of industrial activity is accounted for following the IPCC's representative concentration pathway 8.5 (RCP8.5). The shaded area represents the range from the lowest to the highest predicted temperature. Image Credit: Kay et al. 2015

For example, in figure 4, the steady increase in global average temperature as CO$_2$ concentrations increase dwarfs any variance within the ensemble. Therefore, the forecasted climate change is a strong trend, which can be constrained to a relatively narrow range of expectations.

Overall, internal climate variability is ingrained in the problem of climate prediction, and it cannot be characterized by a single climate model run. However, by generating an ensemble of forecasts, this variability can be understood and accounted for.

Model Development

Given the complex web of considerations and scientific approaches described here, it is natural to wonder how all of this came to be in the first place, and what work within climate prediction looks like now.

To the first question, climate models are mostly produced by universities, as well as national research and forecasting organizations. In the US, this includes the National Center for Atmospheric Research (NCAR) and the National Oceanic and Atmospheric Administration (NOAA). In Europe, notable examples include the European Centre for Medium-range Weather Forecasts (ECMWF) and national weather services like Météo-France. Large groups of researchers and programmers are assembled, each interacting with some part of the model.

As for the current state of the field, climate prediction continues to gain attention as more certain, and sometimes more dire, forecasts are made for the future of Earth's climate. Most climate models are well established, with code bases dating back decades, so improvements are made by improving this base or adding newer, better components to it. Computers continue to become cheaper and more powerful, making for constantly expanding frontiers of what is possible to incorporate into climate models.

Discussion

Returning to the stated goal of this paper— to provide a peek behind the curtain at how the doomsday climate predictions discussed on news channels and social media are made— the previous sections have hopefully provided the tools to better understand where those predictions come from, and the ability to hold both an appreciation for the complex work used to create them, and a healthy dose of skepticism when a headline goes too far beyond what can be predicted with any certainty.

Climate models are useful tools, built on a long legacy of scientific research and understanding, and they provide a powerful, quantitative look into the future. Today, they unequivocally agree that human-caused climate change has begun, and that it will extend for years to come without massive changes in behavior. It is left to the reader to weigh this finding against the many other ways of understanding and grappling with the future, and to decide how to prepare for it.

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