MATHEMATICAL MODELS OF HUMAN-INDUCED GLOBAL CHANGE

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Summary

Complex mathematical models requiring major computing power to tease out their implications are currently the main theoretical tool used to understand and predict the response of the climate system to external forcing, such as that resulting from the current human perturbation to greenhouse gas concentrations in the atmosphere. These models developed quickly over the last half of the 20th century and are in use at several modeling centers around the world. They typically contain sub-models of the atmosphere, land, and ocean, and sometimes also the biosphere. They are used to simulate climate change by imposing an external forcing similar to what the real climate has experienced over the last century and is projected to experience in the coming one. Confidence in their predictions of the gross geographical distribution of temperature change is probably warranted. However, confidence in the overall magnitude of the simulated change is not, mainly due to the current inability to incorporate important climate feedbacks stemming from processes that cannot be explicitly resolved by the models, such as changes in cloudiness as climate warms. The models predict not only a temperature response to increasing greenhouse gas concentrations, but also an increase in the intensity of the global hydrologic cycle. Though there is reason to have some confidence in this global-scale prediction, the simulated regional-scale changes in the

hydrologic cycle are almost certainly not trustworthy. Increasing confidence in model predictions in these critical areas will involve improving the dialogue between model and observations, as well as wise investment of additional computational resources.

1. Introduction

Concern about human influence on climate stems principally from the fact that greenhouse gas concentrations have been increasing in the atmosphere due to human activity for the past two centuries, thereby enhancing the planet's natural greenhouse effect. Since the early 1800's, carbon dioxide (CO_2) concentrations in the atmosphere have increased from 275 to 370 ppm (2002). Mostly attributable to the burning of fossil fuel to power machinery and generate electricity, some of the CO_2 increase is also due to deforestation, which releases carbon stored in the biosphere into the atmosphere. Though the increase in CO_2 comprises the bulk of the current anthropogenic radiative forcing, other greenhouse gases have also increased due to human activity since the beginning of the industrial era, most notably methane (from 750 ppb in 1800 to over 1750 ppb in 2002).

Even those lacking an expertise in climate science can readily see why it is not trivial to predict quantitatively the climate system's temperature response to this external forcing. First, such a prediction requires a detailed understanding of the complicated interactions between solar and terrestrial radiation and certain elements of the climate system. These elements include not only greenhouse gases, but also clouds, snow, sea ice, and vegetation. Second, it requires an understanding of how these elements are distributed. To illustrate how challenging this can be, consider the ubiquitous greenhouse gas water vapor. The distribution of water vapor is impossible to predict reliably without considering the atmosphere's circulation and temperature. To the extent that the atmospheric circulation and temperature change as the climate changes due to a greenhouse gas increase, the water vapor distribution will also change, further altering the greenhouse trapping of the atmosphere and the hence the climate itself. Unraveling the controls on the distribution of clouds, snow, sea ice, and vegetation and their response and feedback to climate change is at least as difficult a task. Third, predicting the magnitude and geographical distribution of the temperature response to an external forcing requires an understanding of the myriad ways in which heat is exchanged and transported within the atmosphere, ocean, and land. For example, the surface temperature at any given location is determined not only by radiative processes, but also by convective transport of heat to higher altitudes, horizontal heat transport through air currents, and latent and sensible heat flux exchange between the lowest portion of the atmosphere and the underlying surface. Moreover, it is clearly desirable to predict not only the temperature response of the climate to an increase in greenhouse gases, but also the alterations in the hydrologic cycle and the biosphere associated with climate change. Achieving these goals requires an understanding of the controls on the geographical distribution of precipitation, evaporation, soil moisture, and ocean circulation.

Since the earth system is so complicated, attempts to understand how its components will respond to external forcing generally require a theoretical approach that is commensurate in complexity. Scientists therefore rely heavily on complex mathematical models for the theoretical component of global change research. These

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models typically represent many processes on a multi-dimensional grid and so require significant computational power to tease out their predictions. Climate observation is of course also critical and is intimately connected with the development of the mathematical models. As with any scientific enterprise, observation is used to compare the predictions of the models against the behavior of the real climate.

2. Historical Development

Because anthropogenic climate change arises from the interaction between radiation and human-induced changes in concentrations of atmospheric constituents, the story of the modeling of global change begins with efforts to understand this process. Then it expands to include efforts to model other processes, first also in the atmosphere, then in the ocean, the land surface, and the biosphere as their relevance of these processes to the climate change problem became clear.

2.1 Early Models

Though he relied on pencil and paper for his calculations rather than a computer, the renowned Swedish physical chemist Svante Arrhenius was the first to use the language of mathematics to make a quantitative estimate of the climate's sensitivity to an increase in greenhouse gases. The paper describing the calculation, published in 1896, was an attempt to explain the transition from the cold ice-age climate of 10,000 years ago to the much warmer climate of the late 19th century, the only global-scale climate variation known at that time. Arrhenius claimed that an increase in CO_2 could have caused such a warming. Though initially focused on explaining past climate change, Arrhenius quickly realized that the burning of fossil fuels, by that time widespread in the industrialized world, could lead to an increase in CO_2 in the atmosphere and a change in climate. In 1904, he wrote, "the slight percentage of carbonic acid [the term used at that time for CO_2] in the atmosphere may, by the advances of industry, be changed to a noticeable degree in the course of a few centuries." In hindsight, Arrhenius' words seem prophetic, though perhaps overly cautious, as the anthropogenic increase in CO_2 became apparent much more quickly than he anticipated.

Arrhenius' model treated the atmosphere as a single slab of material absorbing infrared radiation. As the opacity of this slab to infrared radiation changed due to variations in CO_2, the radiative flux to the surface was altered, resulting in surface temperature changes to maintain radiative equilibrium. This was also the basic theoretical framework underpinning later pioneering modeling studies of climate sensitivity throughout the first two-thirds of the twentieth century by G. Callander, G. Plass, and L. Kaplan. The main advance in these later models was incorporation of an improved understanding of the interaction between CO_2 and infrared radiation. Then, in 1963, F. Möller developed a model that explicitly included the interaction between radiation and atmospheric constituents at multiple levels of the atmosphere, rather than treating the atmosphere as a single slab, as Arrhenius had done. The temperature throughout the atmosphere was calculated by assuming radiative equilibrium at each level. In spite of its enhanced vertical resolution, Möller's model lacked realism in two significant ways: First, it was not able to predict the correct vertical temperature structure of the atmosphere, giving an unrealistically warm surface temperature and a much too steep

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decrease of temperature with altitude. And second, it gave improbably large surface temperature changes on the order of several degrees C for a doubling of CO_2 concentration.

The lack of realism of Möller's model led to major advances in thinking about climate, because it so clearly revealed the flaws in Arrhenius' and others' assumption of pure radiative equilibrium. The gross vertical temperature structure of the atmosphere is not determined only by the interaction of radiation with atmospheric constituents, but also by vertical transport of heat through convection. Convection occurs in the atmosphere when the surface air is lighter than the air above it, taking into account the expansion of air parcels as they rise to higher altitudes and lower pressures. This is precisely the situation in Möller's model: the warm surface air and the steep decrease in temperature with altitude means that the surface air is very light and buoyant relative to the air aloft. To restore gravitational stability, convective overturning would take place, warming the atmosphere aloft and cooling the surface. Taking Möller's model but applying the additional constraint that the atmosphere transports heat vertically to remove gravitational instability, S Manabe and collaborators developed the radiative-convective model. This model has a much more realistic surface and atmospheric temperatures, and a more plausible sensitivity of about a 1°C surface temperature increase to a doubling of CO_2.

In the late 1960s, Manabe and R Wetherald also began to use the radiative-convective model to explore quantitatively whether climate feedbacks might play a role in altering the climate's sensitivity to an external forcing. In the early 20th century others, including T Chamberlin and Arrhenius himself, had identified a process associated with water vapor as probably the most important climate feedback. They argued that an increase in CO_2 would lead to warming, which in turn would lead to an increase in water vapor in the atmosphere, since warmer air can hold more water vapor without becoming saturated. Since water vapor is itself a greenhouse gas, this would enhance the initial warming, leading to still more water vapor in the atmosphere. Manabe and Wetherald attempted to include this water vapor feedback in the radiative-convective model by assuming that the ratio of the water vapor concentration at each level to the saturation concentration of water vapor (i.e. the relative humidity), is a conserved quantity. They found that inclusion of water vapor feedback in this manner approximately doubled the climate sensitivity, so that a 2°C surface temperature increase occurred in response to a doubling of CO_2.

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2.2. Development of GCMs

In parallel with these attempts to model global climate sensitivity with simple one-dimensional models, efforts were made to create mathematical models to predict weather. In the early 1920s by L Richardson grasped the possibility of explicitly solving the equations of fluid motion on a rotating sphere, and so simulating the large-scale movement of air masses and weather systems. However, the problem was intractable, mainly because it required seemingly overwhelming computational power. (Tongue in cheek, Richardson advocated employing tens of thousands of people to carry out the huge numbers of calculations required even for a single weather forecast.) The development of the computer in the 1940s suddenly made Richardson's plan seem less eccentric. By the mid 1950s, weather forecasting using numerical models run on primitive digital computers became routine. Constrained by limited computational resources and used exclusively for weather prediction, these early models made regional rather than global simulations. However, it was soon realized that the same numerical techniques, when extended to the entire globe, could be used to simulate the general circulation of the atmosphere. Such general circulation models---or GCMs---were constructed in the 1960s by Manabe and J Smagorinsky at the Geophysical Fluid Dynamics Laboratory (Princeton NJ USA), A Arakawa and Y Mintz at UCLA, and A Kasahara and W Washington at the National Center for Atmospheric Research in Boulder CO USA. The development of these global models was also facilitated by exponential increases in the speed and performance of digital computers, a trend that continues today. In fact, it is impossible to separate the development of mathematical models of global change from the development of the digital computer. Without the improvements in computing, the advances in mathematical tools to understand global change would have been unimaginable.

Armed with more computational resources and powerful GCMs derived from weather prediction models, scientists were able to focus on fundamental unsolved problems of the atmospheric circulation, including questions relating to climate, such as how heat, moisture and clouds are distributed and transported within the atmosphere. In the early 1970s Manabe realized that the representations of these processes made the GCM a valuable tool to study their role in climate change. Moreover, the GCM provided a three-dimensional global simulation of the climate’s response to an external forcing. This would be a significant advance over the radiative-convective model, which collapsed the entire atmosphere into a single vertical column. In 1975, he and Wetherald published the results of the first CO_2 doubling experiment done with a GCM. The results were similar to what was predicted from the radiative-convective model, except that more warming took place in mid to high latitudes. This was mainly due to decreased snow cover in the warmer climate, which reduced the reflectivity to solar radiation, or albedo, of the high-latitude areas. More sunshine was therefore absorbed which led to warmer temperatures and still greater reduction in snow cover. This study therefore pointed to surface albedo feedback as playing a significant role in determining the geographical distribution of climate response to external forcing.

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Biographical Sketch

Alex Hall, is a professor in the Department of Atmospheric Sciences at the University of California---Los Angeles, where he teaches undergraduate and graduate courses on the earth's climate. He is an expert in climate variability and change and is author of several publications in this area. His research interests include paleoclimate, anthropogenic climate change, the natural climate variability of the southern hemisphere, mesoclimates, and climate model development.

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