THE DEVELOPMENT OF ATMOSPHERIC GENERAL CIRCULATION MODELS

Complexity, Synthesis, and Computation

Over the last fifty years, models that predict the state of the atmosphere have evolved from conceptual frameworks to advanced computational tools for short- and medium-range weather prediction and climate simulation. This book presents a comprehensive discussion of general circulation models of the atmosphere – covering their historical and contemporary development, their societal context, and current efforts to integrate these models into wider Earth system models. Leading researchers provide unique perspectives on the scientific breakthroughs, overarching themes, critical applications, and future prospects for atmospheric general circulation models. Key interdisciplinary links to other subject areas such as chemistry, oceanography, and ecology are also highlighted.

This book is a core reference for academic researchers and professionals involved in atmospheric physics, meteorology, and climate science, and can be used as a resource for graduate-level courses in climate modeling and numerical weather prediction. Given the critical role that atmospheric general circulation models are playing in the intense public discourse on climate change, it is also a valuable resource for policymakers and all those concerned with the scientific basis for the ongoing public-policy debate.

Leo Donner received his Ph.D. in Geophysical Sciences from the University of Chicago in 1983. His research focuses on atmospheric general circulation modeling, especially the treatment of clouds and convective processes. He has served as the science chair of the Global Atmospheric Model Development Team at NOAA's Geophysical Fluid Dynamics Laboratory at Princeton University and a co-chair of the Atmospheric Model Working Group for the Community Atmosphere Model at NCAR in Boulder, Colorado. These models are often regarded as the two leading atmospheric general circulation models for climate studies in the United States. Leo Donner is also a lecturer in the Program in Atmospheric and Oceanic Sciences at Princeton University. He serves on the advisory board for the journal *Tellus* and has been an editor of the *Journal of Climate*.

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Foreword

It has become a commonplace to state that we are in the midst of performing a profound, albeit inadvertent, experiment on the Earth's climate. The need for a virtual Earth upon which we can perform experiments to determine how climate responds to emissions of carbon dioxide and other agents of climate change, to inform mitigation and adaptation decisions, is acknowledged as one of the great challenges to science. This collection of essays provides diverse perspectives on the evolution over time of models that have been developed for climate simulation, what they are capable of today, and what some of the challenges are for the future.

Numerical weather prediction provided the starting point for this evolution, with the realization immediately following the invention of computers that weather prediction was a perfect application for this new technology. Atmospheric models evolved rapidly with practical impetus from the needs of weather prediction. Atmospheric general circulation models then evolved from this base as it was realized that one could integrate these systems for arbitrarily long time intervals, gathering statistics of the weather thereby generated, producing simulation of our climate.

From this starting point, focused on the fluid dynamics of the atmosphere, climate models have steadily grown in comprehensiveness and complexity. Ocean models developed later than their atmospheric counterparts, and have presented many distinctive challenges for simulations, most fundamentally due to the sparseness of observations but also because the energy-containing scales of motion are smaller in the oceans, creating an especially challenging computational problem. Ocean models have taken on the added complexity of the cycling of carbon, nitrogen, oxygen, and other elements needed to understand how oceanic biology, and the uptake of carbon by the oceans, will evolve in the future. Land models have more recently increased in realism driven by the need to estimate how the uptake of carbon by land vegetation will evolve and how the hydrological cycle over land responds to climate change. Models of the cryosphere initially tackled the problem of modeling sea ice in the Arctic and Antarctic, and are now focusing on the challenging problem of incorporating the Greenland and Antarctic ice sheets into comprehensive models. Meanwhile atmospheric models have taken on the task of simulating atmospheric chemistry, both in the stratosphere, where a key interest is the distribution of ozone, and the troposphere, with a focus on the ability to simulate the species of relevance to air quality. Modeling particulates in the atmosphere, diverse in their composition, chemistry, and sources, has taken on a special urgency due to the potential for aerosol pollution to mask the effects of increasing greenhouse gases, and for the importance of aerosol/cloud interactions. Simultaneously with this evolution towards greater comprehensiveness, all of these components of our “Earth system models” are evolving towards finer resolution as fast as computational resources allow.

Our climate models have suggested and refined many of the basic tenets on which our understanding of climate change and variability are built. These include: the inability of internal variability to explain the observed twentieth century warming; the existence of a robust and strong water vapor feedback; the increase in precipitation in subpolar latitudes and decrease in the subtropics as the climate warms; and the manner in which the deep oceans take up heat and delay the full equilibration of climate to a perturbation for centuries, even millennia. Ongoing research is making progress on difficult questions such as how changes in the stratosphere affect the tropospheric circulation, how phenomena such as El Niño, Atlantic hurricanes, or the dynamic pole-to-pole circulation in the Atlantic Ocean will react to warming. There are other crucial questions, such as how the cloud cover will respond to warming, how the Greenland and Antarctic ice sheets will respond, how rainfall will change on the small scales of most relevance to agriculture and water resources, and how the uptake of carbon by the land surface will change, for which compelling projections remain elusive. The credibility of climate simulations is steadily increasing. By normal standards, this performance would be considered exemplary, but in our present predicament more is required.

Given the dramatic increase in complexity of climate models, and the pressures that exist to improve simulations rapidly, it should come as no surprise that there is uncertainty within the climate modeling community concerning the best course for the future. I mention a few of these concerns here, which the reader may wish to keep in mind when studying these essays.

The climate modeling enterprise today is dominated by a few large groups with substantial computational resources at their disposal. The rise in complexity has encouraged this trend towards “big science”, in that a diverse range of expertise is clearly needed to incorporate many diverse processes into these models.

Additionally, both because of the heterogeneity of the land surface and because atmospheric and oceanic flows are turbulent with a wide range of relevant scales of motion, climate models typically improve as they move to finer spatial resolutions, encouraging the use of the largest computers in existence for these simulations. As a result of these tendencies, is the field of climate modeling becoming too monolithic, thereby stifling innovation? Should there be a greater effort to create frameworks within which a much larger community of researchers can contribute, perhaps patterned after the open-source movement in software development?

It is not uncommon for groups to organize their effort in a modular fashion, with sub-groups around the world contributing individual sub-components. But when one connects different sub-components together, there are invariably issues with the resulting simulation; otherwise the problem would effectively have been solved. Say, for example, that one finds that the simulation of the frequency or structure of El Niño events that emerges from the model is unrealistic. Is the problem in the treatment of small-scale atmospheric moist convection, the stratus cloud formulation, the mixing scheme used in the ocean model, the surface flux computation, the resolution of details of the ocean basin geometry controlling the flow of water from the Pacific to the Indian Ocean, or the way in which the solar flux absorbed in the upper ocean is affected by the transparency of the water as controlled by phytoplankton distributions? (There is literature on each of these processes affecting El Niño simulations.) It is more difficult to distribute model development broadly when it requires a holistic understanding that can only be developed by experimenting with the full system as opposed to individual components.

The increasing complexity of climate models creates problems in communication and education. The world is vitally interested in the results of these simulations, but few understand what a climate model is, or what the strengths and weaknesses of today's models are. Even students desiring to work with and develop climate models have difficulty getting their minds around the full complexity of these models. There is a clear pedagogical need for a hierarchy of models of increasing complexity, and there is much work along these lines. Indeed, it has been argued that such a hierarchy is fundamental to understanding the behavior of these complex models and that this understanding is crucial for creating an efficient model improvement process.

The analogy with biology is useful in this context. Evolution provides the biologist with a natural hierarchy of systems to study, ranging from the simplest bacteria to humans. We do not have a hierarchy of climates of increasing complexity handed to us by nature. Planetary atmospheres are too few and, as a result, too idiosyncratic. Laboratory simulations relevant for most issues in climate research are not possible. Climate scientists must create their own model hierarchies. Does the continuing development of models with more and more interactive components eventually become untenable without the solid foundations provided by the careful analysis of a hierarchy of simpler models?

Should climate models try to build steadily on the unquestioned successes of numerical weather prediction, focusing, for example, on improving seasonal predictions of El Niño and then moving systematically on to prediction of decadal climate variations? Many nations have at least partially integrated their numerical weather prediction and climate modeling efforts. After all, it is the same system that is being simulated in both cases. Some convergence is natural, especially as climate modelers focus on shorter time-scales and prediction efforts move to longer time-scales.

But beyond a couple of decades, we no longer have the luxury of the time needed to accumulate a useful set of forecasts for model validation. Additionally, as time-scales lengthen the prediction problem becomes one of determining the forced response to external perturbations rather than the evolution of internal variability from specific initial conditions. If one is interested in how the El Niño phenomenon will change in the future, is one better off focusing on improving predictions of El Niño or on improving the climatological structure of El Niño variability? If one is close to the final answer, there should be no conflict between these two objectives. If, hypothetically, there is only one uncertain parameter that remains to be determined, with all other aspects of the model perfected, then the same value of this parameter will optimize any metric of interest. But if there is still substantial uncertainty concerning how best to encompass all of the factors that effect the El Niño phenomenon in models, one can easily envision a distinction between model settings that optimize seasonal predictions and settings that optimize long-term El Niño statistics.

The climate-change problem is also distinctive as compared to numerical weather prediction in the importance placed on the attribution of past changes. If one can extract the response to increasing greenhouse gases from observations of the recent past, one can test models of this forced response and, in the simplest case, extrapolate into the future. The attribution problem and the prediction problem then become effectively synonymous. This importance of attribution is not found in weather prediction. Simulations of paleoclimates also play a fundamental role in testing climate models in a way that has no counterpart in standard weather prediction. These are some of the reasons why weather prediction and climate models might diverge and why climate modeling and numerical weather prediction groups might require differing expertise.

Climate researchers face challenges in a host of research areas examining climate-relevant processes in the atmosphere, in the oceans, and on land. Climate modelers also face challenges on more holistic levels in understanding how these processes interact in all their complexity to create our climate and control its sensitivity. And there are challenges with regard to how nations, and the world, should structure their modeling efforts, and on how to communicate results and limitations most effectively with the public and policymakers. These are clearly exciting and challenging times for the climate modeling enterprise.

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