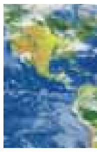
CHAPTER 1

Introduction



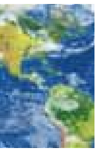
The use of computers to simulate complex systems has grown in the past few decades to play a central role in many areas of science. Climate modeling is one of the best examples of this trend and one of the great success stories of scientific simulation. Building a laboratory analog of the Earth's climate system with all its complexity is impossible. Instead, the successes of climate modeling allow us to address many questions about climate by experimenting with simulations—that is, with mathematical models of the climate system. Despite the success of the climate modeling enterprise, the complexity of our Earth imposes important limitations on existing climate models. This report aims to help the reader understand the valid uses, as well as the limitations, of current climate models.

Climate modeling and forecasting grew from the desire to predict weather. The distinction between climate and weather is not precise. Operational weather forecasting has focused historically on time scales of a few days but more recently has been extended to months and seasons in attempts to predict the evolution of El Niño episodes. The goal of climate modeling can be thought of as the extension of forecasting to longer and longer time periods. The focus is not on individual weather events, which are unpredictable on long time scales, but on the statistics of these events and on the slow evolution of oceans and ice sheets. Whether the forecasting of individual El Niño episodes is considered weather or climate is a matter of convention. For the purpose of this report, we will consider El Niño forecasting as weather and will not address it directly. On the climate side we are concerned, for example, with the ability of models to simulate the statistical characteristics of El Niño variability or extratropical storms or Atlantic hurricanes, with an eye toward assessing the ability of models to predict how variability might change as the climate evolves in coming decades and centuries.

An important constraint on climate models not imposed on weather-forecast models is the requirement that the global system precisely and accurately maintain the global energy balance over very long periods of time. The Earth's energy balance (or "budget") is defined as the difference between absorbed solar energy and emitted infrared radiation to space. It is affected by many factors, including the accumulation of greenhouse gases, such as carbon dioxide, in the atmosphere. The decades-to-century changes in the Earth's energy budget, manifested as climate changes, are just a few percent of the average values of that budget's largest terms. Many decisions about model construction described in

Chapter 2 are based on the need to properly and accurately simulate the long-term energy balance.

This report will focus primarily on comprehensive physical climate models used for the most recent international Coupled Model Intercomparison Project (CMIP) coordinated experiments (Meehl et al. 2006) sponsored by the World Climate Research Programme (WCRP). These coupled atmosphere-ocean general circulation models (AOGCMs) incorporate detailed representations of the atmosphere, land surface, oceans, and sea ice. Where practical, we will emphasize and highlight results from the three U.S. modeling projects that participated in the CMIP experiments. Additionally, this report examines the use of regional climate models (RCMs) for obtaining higher-resolution details from AOGCM simulations over smaller regions. Still, other types of climate models are being developed and applied to climate simulation. The more-complete Earth system models, which build carbon-cycle and ecosystem processes on top of AOGCMs, are used primarily for studies of future climate change and paleoclimatology, neither of which is directly relevant to this report. Another class of models not discussed here but used extensively, particularly when computer resources are limited, is Earth system models of intermediate complexity (EMICs). Although these models have many more assumptions and simplifications than are found in CMIP models (Claussen et al. 2002), they are particularly useful in exploring a wide range of mechanisms and obtaining broad estimates of future climate change projections that can be further refined with AOGCM experiments.

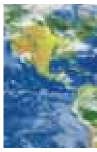


1.1 BRIEF HISTORY OF CLIMATE MODEL DEVELOPMENT

As numerical weather prediction was developing in the 1950s as one of the first computer applications, the possibility of also using numerical simulation to study climate became evident almost immediately. The feasibility of generating stable integrations of atmospheric equations for arbitrarily long time periods was demonstrated by Norman Phillips in 1956. About that time, Joseph Smagorinsky started a program in climate modeling that ultimately became one of the most vigorous and longest-lived GCM development programs at the National Oceanic and Atmospheric Administration's Geophysical Fluid Dynamics Laboratory (GFDL) at Princeton University. The University of California at Los Angeles began producing atmospheric general circulation models (AGCMs) beginning in 1961 under the leadership of Yale Mintz and Akio Arakawa. This program influenced others in the 1960s and 1970s, leading to modeling programs found today at National Aeronautics and Space Administration (NASA) laboratories and several universities. At Lawrence Livermore National Laboratory, Cecil E. Leith developed an early AGCM in 1964. The U.S. National Center for Atmospheric Research (NCAR) initiated AGCM development in 1964 under Akira Kasahara and Warren Washington. Leith moved to NCAR in the late 1960s and, in the early 1980s, oversaw construction of the Community Climate Model, a predecessor to the present Community Climate System Model (CCSM).

Early weather models focused on fluid dynamics rather than on radiative transfer and the atmosphere's energy budget, which are centrally important for climate simulations. Additions to the original AGCMs used for weather analysis and prediction were needed to make climate simulations possible. Furthermore, because climate simulation focuses on time scales longer than a season, oceans and sea ice must be included in the modeling system in addition to the more rapidly evolving atmosphere. Thus, ocean and ice models have been coupled with atmospheric models. The first ocean GCMs were developed at GFDL by Bryan and Cox in the 1960s and then coupled with the atmosphere by Manabe and Bryan in the 1970s. Paralleling events in the United States, the 1960s and 1970s also were a period of climate- and weather-model development throughout the world, with major centers emerging in Europe and Asia. Representatives of these groups gathered in Stockholm in August 1974, under the sponsorship of the Global Atmospheric Research Programme to produce a seminal treatise on climate modeling (GARP 1975). This meeting established collaborations that still promote international cooperation today.

The use of climate models in research on carbon dioxide and climate began in the early 1970s. The important study, “Inadvertent Climate Modification” (SMIC 1971), endorsed the use of GCM-based climate models to study the possibility of anthropogenic climate change. With continued improvements in both climate observations and computer power, modeling groups furthered their models through steady but incremental improvements. By the late1980s, several national and international organizations formed to assess and expand scientific research related to global climate change. These developments spurred interest in accelerating the development of improved climate models. The primary focus of Working Group 1 of the United Nations Intergovernmental Panel on Climate Change (IPCC), which began in 1988, was the scientific inquiry into physical processes governing climate change. IPCC’s first Scientific Assessment (IPCC 1990) stated, “Improved prediction of climate change depends on the development of climate models, which is the objective of the climate modeling programme of the World Climate Research Programme.” The United States Global Change Research Program (USGCRP), established in 1989, designated climate modeling and prediction as one of the four high-priority integrating themes of the program (Our Changing Planet 1991). The combination of steadily increasing computer power and research spurred by WCRP and USGCRP has led to a steady improvement in the completeness, accuracy, and resolution of AOGCMS for climate simulation and prediction. An often-used illustration from the Third IPCC Working Group 1 *Scientific Assessment of Climate Change* in 2001 depicts this evolution (see Fig. 1.1). Even more comprehensive climate models produced a series of coordinated numerical simulations for the third international Climate Model Intercomparison Project (CMIP3), which were used extensively in research cited in the recent Fourth IPCC Assessment (IPCC 2007). Contributions came from three groups in the United States (GFDL, NCAR, and the NASA Goddard Institute for Space Studies) and others in the United Kingdom, Germany, France, Japan, Australia, Canada, Russia, China, Korea, and Norway.



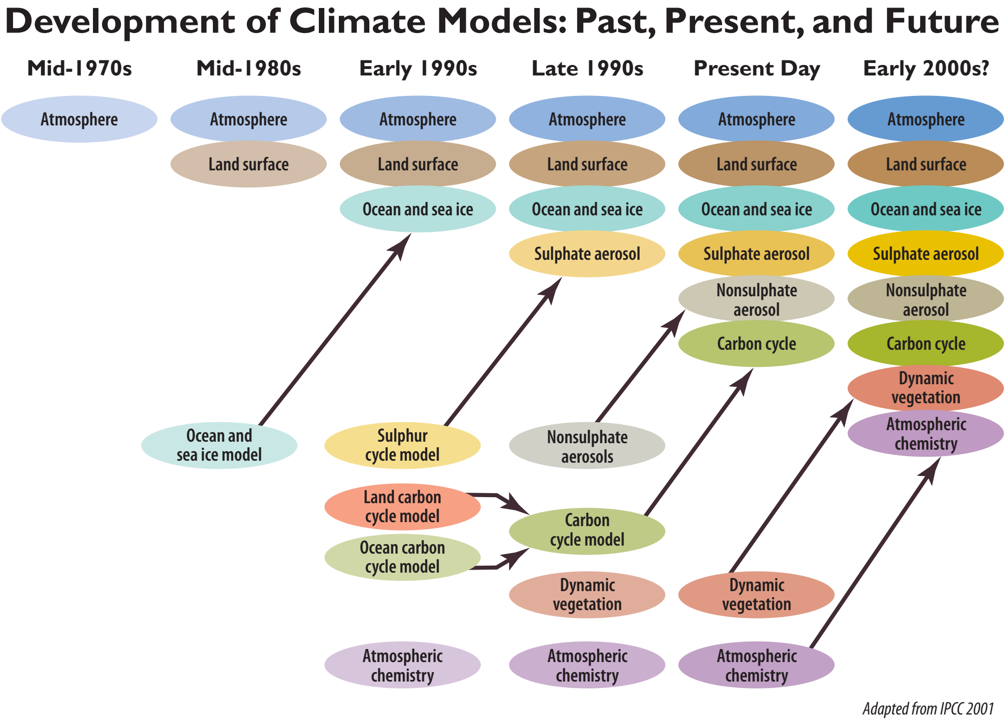
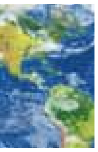


Figure 1.1. Historical Development of Climate Models.

[Figure source: *Climate Change 2001: The Scientific Basis, Contribution of Working Group 1 to the Assessment Report of the Intergovernmental Panel on Climate Change*, p. 48. Used with permission from IPCC.]

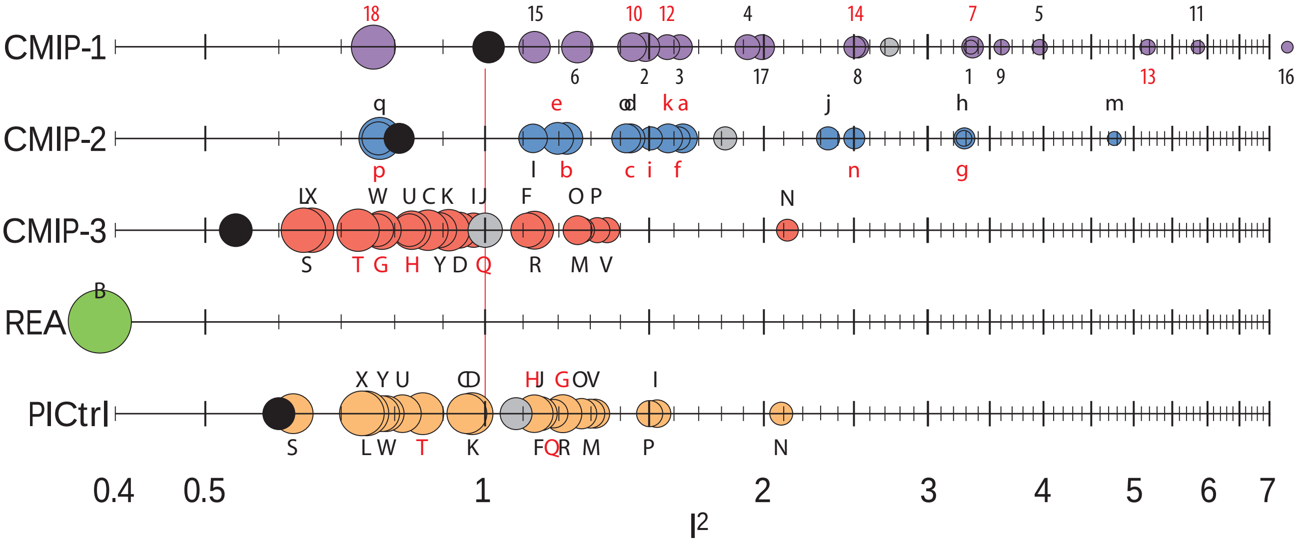
1.2 CLIMATE MODEL CONSTRUCTION



Comprehensive climate models are constructed using expert judgments to satisfy many constraints and requirements. Overarching considerations are the accurate simulation of the most important climate features and the scientific understanding of the processes that control these features. Typically, the basic requirement is that models should simulate features important to humans, particularly surface variables such as temperature, precipitation, windiness, and storminess. This is a less-straightforward requirement than it seems because a physically based climate model also must simulate all complex interactions in the coupled atmosphere–ocean–land surface–ice system manifested as climate variables of interest. For example, jet streams at altitudes of 10 km above the surface must be simulated accurately if models are to generate midlatitude weather with realistic characteristics. Midlatitude highs and lows shown on surface weather maps are intimately associated with these high-altitude wind patterns. As another example, the basic temperature decrease from the equator to the poles cannot be simulated without taking into account the poleward transport of heat in the oceans, some of this heat being carried by currents 2 or 3 km deep into the ocean interior. Thus, comprehensive models should produce correctly not just the means of variables of interest but also the extremes and other measures of natural variability. Finally, our models should be capable of simulating changes in statistics caused by relatively small changes in the Earth's energy budget that result from natural and human actions.

Climate processes operate on time scales ranging from several hours to millennia and on spatial scales ranging from a few centimeters to thousands of kilometers. Principles of scale analysis, fluid dynamical filtering, and numerical analysis are used for intelligent compromises and approximations to make possible the formulation of mathematical representations of processes and their interactions. These mathematical models are then translated into computer codes executed on some of the most powerful computers in the world. Available computer power helps determine the types of approximations required. As a general rule, growth of computational resources allows modelers to formulate algorithms less dependent on approximations known to have limitations, thereby producing simulations more solidly founded on established physical principles. These approximations are most often found in "closure" or "parameterization" schemes that take into account unresolved motions and processes and are always required because climate simulations must be designed so they can be completed and analyzed by scientists in a timely manner, even if run on the most powerful computers.

Climate models have shown steady improvement over time as computer power has increased, our understanding of physical processes of climatic relevance has grown, datasets useful for model evaluation have been developed, and our computational algorithms have improved. Figure 1.2 shows one attempt at quantifying this change. It compares a particular metric of climate model performance among the CMIP1 (1995), CMIP2 (1997), and CMIP3 (2004) ensembles of AOGCMs. This particular metric assesses model performance in simulating the mean climate of the late 20th Century as measured by a basket of indicators focusing on aspects of atmospheric climate for which observational counterparts are deemed adequate. Model ranking according to individual members of this basket of indicators varies greatly, so this aggregate ranking depends on how different indicators are weighted in relative importance. Nevertheless, the conclusion that models have improved over time is not dependent on the relative weighting factors, as nearly all models have improved in most respects. The construction of metrics for evaluating climate models is itself a subject of intensive research and will be covered in more detail in Chapter 2.



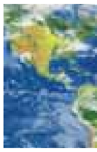


Figure 1.2. Performance Index I^2 for Individual Models (circles) and Model Generations (rows).

Best performing models have low I^2 values and are located toward the left. Circle sizes indicate the length of the 95% confidence intervals. Letters and numbers identify individual models; flux corrected models are labeled in red. Grey circles show the average I^2 of all models within one model group. Black circles indicate the I^2 of the multimodel mean taken over one model group. The green circle (REA) corresponds to the I^2 of the NCEP/NCAR Reanalysis (Kalnay et al. 1996), conducted by the National Weather Service's National Centers for Environmental Prediction and the National Center for Atmospheric Research. Last row (PICTRL) shows I^2 for the preindustrial control experiment of the CMIP3 project. [Adapted from Fig. 1 in T. Reichler and J. Kim 2008: How well do coupled models simulate today's climate? *Bulletin American Meteorological Society*, **89**(3), doi:10.1175/BAMS-89-3-303. Reproduced by permission of the American Meteorological Society.]

Also shown in Fig. 1.2 is the same metric evaluated from climate simulation results obtained by averaging over all AOGCMs in the CMIP1, CMIP2, and CMIP3 archives. The CMIP3 "ensemble-mean" model performs better than any individual model by this metric and by many others. This kind of result has convinced the community of the value of a multimodel approach to climate change projection. Our understanding of climate is still insufficient to justify proclaiming any one model "best" or even showing metrics of model performance that imply skill in predicting the future. More appropriate in any assessments focusing on adaptation or mitigation strategies is to take into account, in a pertinently informed manner, the products of distinct models built using different expert judgments at centers around the world.

1.3 SUMMARY OF SAP 3.1 CHAPTERS

The remaining sections of this report describe climate model development, evaluation, and applications in more detail. Chapter 2 describes the development and construction of models and how they are employed for climate research. Chapter 3 discusses regional climate models and their use in "downscaling" global model results to specific geographic regions, particularly North America. The concept of climate sensitivity—the response of a surface temperature to a specified change in the energy budget at the top of the model's atmosphere—is described in Chapter 4. A survey of how well important climate features are simulated by modern models is found in Chapter 5, while Chapter 6 depicts near-term development priorities for future model development. Finally, Chapter 7 illustrates a few examples of how climate model simulations are used for practical applications. A detailed Reference section follows Chapter 7.