Chapter I – 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. It is impossible to build a laboratory analog of the Earth's climate system with all of its complexity. The successes of climate modeling allow us to address many questions about the climate by experimenting instead 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. It is the purpose of this report to help the reader understand the valid uses, as well as the limitations, of current climate models.

Climate modeling and forecasting grew out of the desire to predict weather. The distinction between climate and weather is not sharp. Operational weather forecasting has historically focused on times scales of a few days but has more recently been extended to monthly and seasonal time scales, for example, 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 scales, with a focus not on individual weather events, which are unpredictable on these long time scales, but on the statistics of these events as well as on the slow evolution of the oceans and ice sheets. Whether one considers the forecasting of individual El Niño episodes as weather or climate forecasting is a matter of convention. For the purpose of this report, we will consider El Nino forecasting with 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 these models to predict how this variability might change as the climate evolves in the coming decades and centuries.

An important constraint required of climate models that is not imposed on weather forecast models is the requirement that the global system precisely and accurately maintain the global energy balance over very long time periods. Energy balance (or "budget") is defined as the difference between absorbed solar energy and emitted infrared radiation. It is affected by a number of things including human production of greenhouse gases like carbon dioxide. The decadal to century-scale changes in the Earth’s energy budget that are manifested as climate change are just a few per cent of the average values of the largest terms in that budget. Many of the decisions about model construction described in Chapter II are based on the need to properly and accurately simulate the long term energy balance.

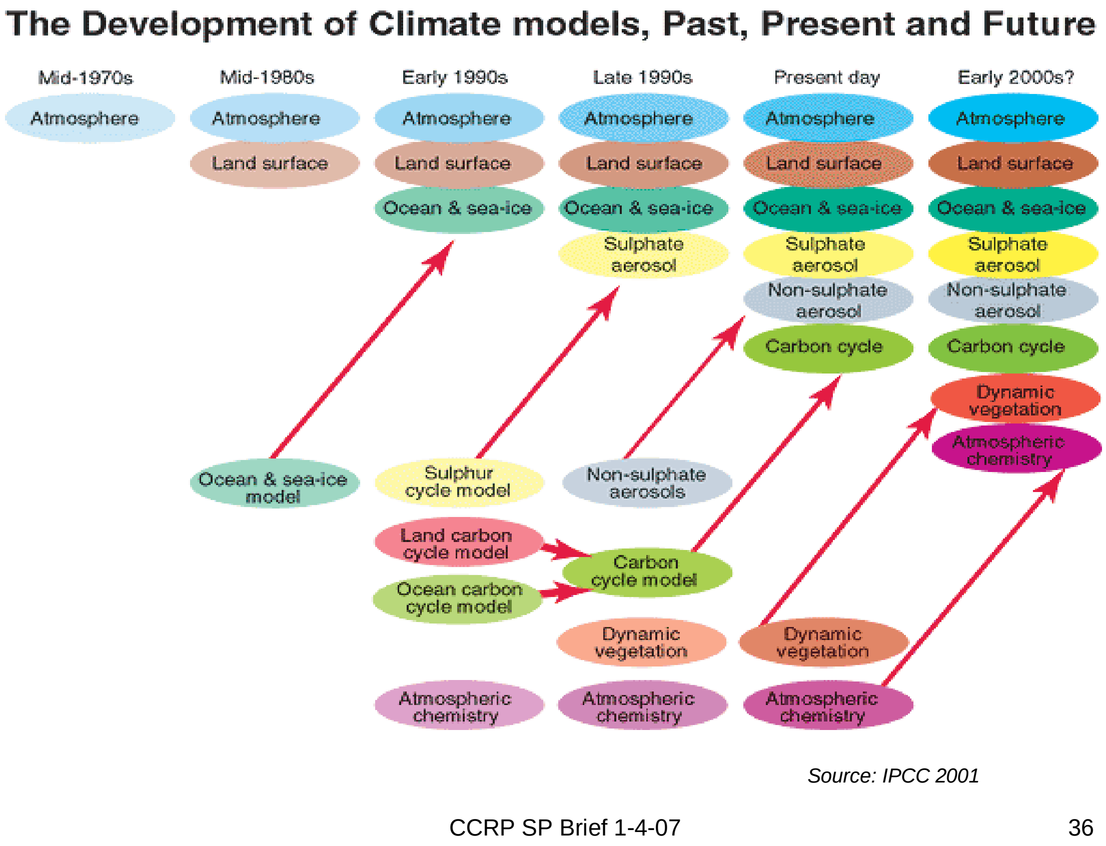
This report will focus primarily on the most advanced physical climate models that were used for the most recent international Coupled Model Intercomparison Project’s (CMIP) coordinated experiments (Meehl, *et al*., 2006), sponsored by the World Climate Research Programme (WCRP). These coupled Atmosphere–Ocean General Circulation Models (AOGCMs) incorporate detailed representations of the atmosphere, land surface, oceans, and sea ice. Where practical, we will emphasize and highlight the results from the three US modeling projects that participated in the CMIP experiments. Additionally, this report examines the use of Regional Climate Models used for obtaining higher resolution details from AOGCM simulations over smaller regions. Nevertheless, it must be noted that there are other types of climate models being developed and applied to climate simulation. More complete Earth systems models build carbon cycle and ecosystems processes on top of the AOGCMs, but are employed more 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, are Earth-system Models of Intermediate Complexity (EMICs). Although these models have many more assumptions and simplifications than are found in the CMIP models (Claussen *et a*l., 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.

Brief History of Climate Model Development

As the possibility of numerical weather prediction developed in the 1950’s as one of the first applications of computers, it became evident almost immediately that the numerical simulation approach could also be used to study the climate. In 1955, Joseph Smagorinsky started a program in climate modeling that ultimately became one of the most vigorous and longest-lived General Circulation Model (GCM) development programs at NOAA’s Geophysical Fluid Dynamics Laboratory (GFDL) at Princeton University. The feasibility of generating stable integrations of the atmospheric equations for arbitrarily long time periods was demonstrated by Norman Phillips in 1956. 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 1960’s and 1970’s, leading to modeling programs found today at NASA laboratories and several universities. At Lawrence Livermore National Laboratory, Cecil E. Leith developed an AGCM in the early and mid-1960's. The U.S. National Center for Atmospheric Research (NCAR) initiated AGCM development in 1964 under Akira Kasahara and Warren Washington, an effort that ultimately evolved into the construction of the Community Climate Model, a predecessor to the present Community Climate System Model. Also in the 1960’s and 70’s, efforts in climate simulations developed throughout the world, with major centers emerging in Europe and Asia.

Additions to the original atmospheric general circulation models used for weather analysis and prediction were needed to improve weather simulations and forecasts as well as to make climate simulations possible. The early weather models focused on fluid dynamics rather than on radiative transfer and the atmosphere’s energy budget, which are of central importance for climate simulations. Furthermore, as one focuses on time scales longer than a season, the oceans and sea ice must be coupled to the more rapidly evolving atmosphere. Thus, ocean and ice models have been coupled with atmospheric models. The first ocean general circulation models were developed at GFDL by Bryan and Cox in the 1960’s, and then coupled with the atmosphere by Manabe and Bryan in the 1970’s.

Climate models began to be used in research on carbon dioxide and climate in the mid-1970’s. Two important studies, the *Study of Critical Environmental Problems* and the *Study of Man’s Impact on Climate*, both endorsed the use of GCM-based climate models to study the possibility of anthropogenic climate change. Beginning in the late 1980’s, several national and international organizations were formed with the purpose of assessing and expanding scientific research related to global climate change. These developments spurred interest in developing and improving climate models. The work of the Intergovernmental Panel on Climate Change (IPCC), beginning in 1987, had as a primary focus of Working Group 1 scientific inquiry into atmospheric processes governing climate change. The **IPCC**,1990: *Scientific Assessment* (Houghton *et al*., 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 (WCRP).” 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 (CEES, 1991). The combination of steadily increasing computer power and research spurred by the WCRP and USGCRP has led to a steady improvement in the completeness, accuracy and resolution of AOGCMS used for climate simulation and prediction. A classic figure from the Third IPCC Working Group I Scientific Assessment of Climate Change in 2001 depicts this evolution in **Figure I.A.** The comprehensive climate models that contributed results to the Third Climate Model Intercomparison Project (CMIP3) that was utilized by the Fourth IPCC Assessment were generated by 3 groups in the US (GFDL, NCAR, and the NASA Goddard Institute for Space Studies (GISS)), and groups in the U.K., Germany, France, Japan, Australia, Canada, Russia, China, Korea, and Norway.



Source: IPCC 2001

Figure.I.A Historical development of climate models (From IPCC, 2001).

Climate model construction

Comprehensive climate models are constructed using expert judgments to satisfy many constraints and requirements. The overarching considerations are the determination of the most important climate features that should be accurately simulated and the scientific understanding of these features that guide one towards the most powerful simulation strategies and algorithms. Typically, the basic requirement is that models should simulate features that are important to humans, particularly surface variables, such as temperature, precipitation, windiness, and storminess. This is a less straightforward requirement than it seems, since a physically-based climate model must also simulate all of the complex interactions in the coupled atmosphere–ocean–land surface–ice system that are manifested as the climate variables of interest. For example, jet streams at altitudes of 10 kilometers above the surface must be accurately simulated if the models are to generate midlatitude weather with realistic characteristics, since the midlatitude highs and lows that we see on surface weather maps are intimately associated with these high-altitude wind patterns. As another example, one cannot simulate the basic temperature decrease from the equator to the poles without taking into account the poleward transport of heat in the oceans, some of this heat being carried by currents 2 or 3 kms deep in the oceanic interior. Our models should correctly produce not just the means of variables of interest, but also extremes and other measures of natural variability. Finally, they should be capable of simulating the changes in those statistics that result from the 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 spatial scales ranging from a few centimeters to thousands of kilometers. Principles of scale analysis, fluid dynamical filtering, and numerical analysis are used to make intelligent compromises and approximations to simplify the system sufficiently to make it tractable to formulate mathematical representations of the processes and their interactions. These mathematical models are then translated into computer codes, which are 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, increasing computational resources allows modelers to formulate algorithms that are less dependent on relatively uncertain methods (referred to as "closure" or "parameterization" schemes) for taking into account unresolved motions and processes, thereby producing simulations that are more solidly founded on established physical principles. Climate simulations must always be designed so that they can be completed and analyzed by scientists in a timely manner.

Climate models have shown steady improvement over time as computer power has increased, as our understanding of physical processes of climatic relevance has increased, as data sets useful for model evaluation have been developed, and as our computational algorithms have improved. **Figure I.B** shows one attempt at quantifying this improvement. 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 the performance of the models in simulating the mean climate of the late 20th century as measured by a basket of indicators, focusing on aspects of the atmospheric climate for which observational counterparts are deemed adequate for this purpose. The ranking of models according to individual members of this basket of indicators varies greatly, so this aggregate ranking is dependent on how one weights the relative importance of different indicators. But the general conclusion of an improvement in climate simulation quality is robust to these changes in weighting factors. The construction of metrics for evaluating climate models is itself a subject of intensive research and will be covered in more detail in Chapter II.

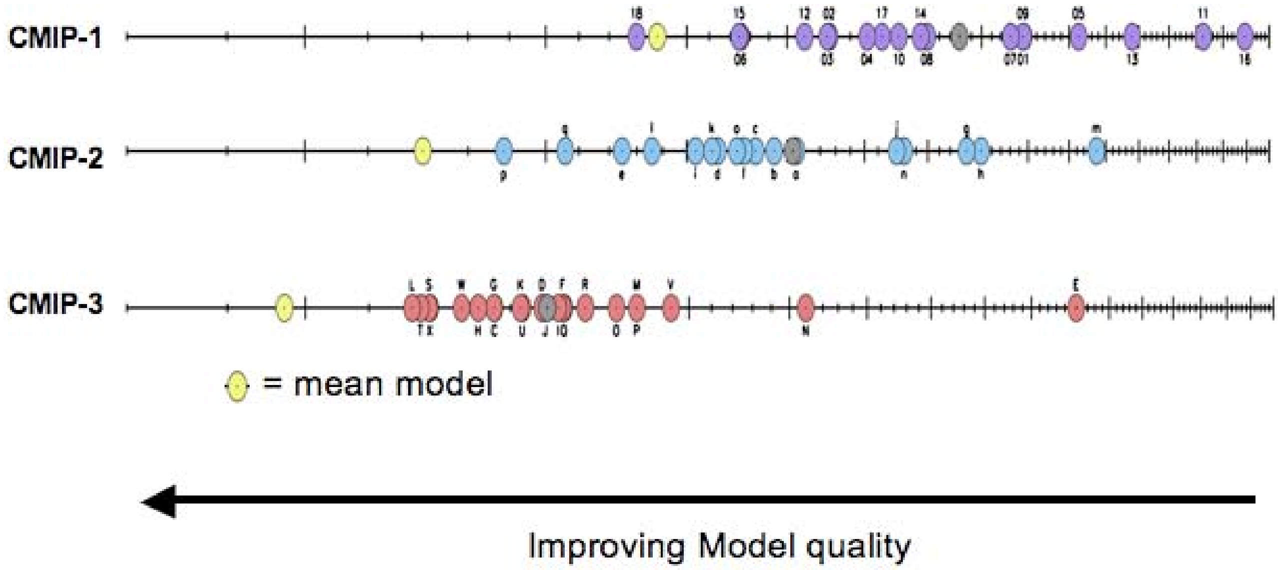


Figure.I.B One possible composite metric for the evaluation of climate models, focusing primarily on the atmospheric circulation (Kim and Riechler, 2007,, baased on PCMDI CMIP-1, CMIP-2, and CMIP-3 archives Each oval corresponds to a single model, with model quality improving towards the left. Yellow ovals mark the quality of the climate obtained by averaging all of the available models. The CMIP-1 model archive was generated from models available around1995, the CMIP-2 models around 2000, and the CMIP-3 models around 2005.

Also, shown in **Figure I.B** is the same metric evaluated from the climate obtained by averaging over all of the 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, at this point in time, of a multi-model approach to climate change projection, in which a number of modeling centers work on their own distinctive approaches to the fundamental fluid dynamical simulation problem as well as the many issues related to the parameterization of unresolved processes. Our understanding of climate is still insufficient to justify the construction or identification of a single model that we can confidently judge to be the best possible model. It is generally felt to be more appropriate, in any assessments focusing on adaptation or mitigation strategies, to take into account, in an appropriately informed manner, the attempts at climate simulation underway around the world.

The remaining sections of this report describe climate model development, evaluation and applications in more detail. Chapter II describe the development and construction of models and how they are employed for climate research. Chapter III discusses Regional Climate Models and their use in "downscaling" global model results to specific geographic regions, particularly North America. The concept of climate sensitivity, which is 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 IV. A survey of how well important climate features are simulated by modern models is found in Chapter V, while Chapter VI depicts the near-term development priorities for future model development. Finally, Chapter VII illustrates a few examples of how climate model simulations are used for practical applications. A detailed References section follows Chapter VII.