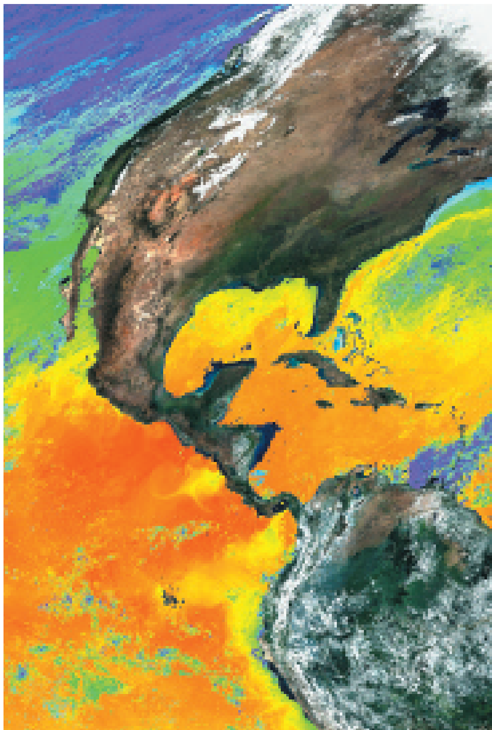
10 CHAPTER

Modeling Strategy



CHAPTER CONTENTS

This chapter introduces goals and objectives intended to provide accelerated scientific improvements in climate and climate impact models responsive to the needs of the Climate Change Science Program's (CCSP) scientific research and decision support activities.

Models are essential tools for synthesizing observations, theory, and experimental results to investigate how the Earth system works and how it is affected by human activities. Models can be used in both a retrospective sense, to test the accuracy of modeled changes in Earth system forcing and response by comparing model results with observations of past change, and in a prognostic sense, for calculating the response of the Earth system to projected future forcing. Comprehensive climate system models provide the primary quantitative means to integrate scientific understanding of the many components of the climate system and, thus, are the principal tools available for making quantitative projections.

The CCSP modeling strategy consists of three goals: Improve the scientific basis of climate and climate impacts models; provide the infrastructure and capacity necessary to support a scientifically rigorous and responsive U.S. climate modeling activity; and coordinate and accelerate climate modeling activities and provide relevant decision support information on a timely basis. In order to achieve these goals, three modeling arenas will be implemented: (1) diverse and disparate research activities that represent new process understanding in models; (2) assimilation and integration efforts that employ new types of observations and tools and next-generation understanding and model coupling; and (3) "high-end" climate models run for scenarios required in periodic scientific assessments or to achieve higher resolutions.

The CCSP strategy envisions two complementary streams of climate modeling activities. The first is principally a research activity, which will maintain strong ties to the global change and computational science research communities to rapidly incorporate new knowledge into a comprehensive climate and Earth system modeling capability. Closely associated with the research activity, but distinct from it, will be the sustained and timely delivery of predictive model products that are required for assessments and other decision support needs. CCSP will ensure that a productive partnership is maintained between product-driven modeling activities and the discovery-driven modeling research program that will underpin its credibility and future success.

In his 11 June 2001 speech, the President asked his Administration to work to "develop state-of-the-art climate modeling that will help us better understand the causes and impacts of climate change." In response to this directive, the program is addressing the following overarching question:

> ***How can we most effectively accelerate the development, testing, and application of the best possible scientifically based climate and climate impact models to serve scientific research and decision support needs?***

Based on recommendations in National Research Council (NRC) reports on U.S. climate modeling (NRC, 1999b, 2001d), the CCSP agencies initiated new activities to strengthen the national climate modeling infrastructure. These activities will accelerate the delivery of improved model products that are especially important for making climate simulations, predictions, and projections more usable and applicable to the broader research, assessment, and policy communities (see Annex D for definitions of climate "prediction" and "projection"). The new activities form the basis of a longer term solution that will maintain the pace and progress of the basic research, while simultaneously creating a path for the rapid exploitation of new knowledge in model development, testing, and applications.

Goal 1: Improve the scientific basis of climate and climate impacts models.

Virtually all comprehensive climate models project a warmer Earth, an intensified hydrologic cycle, and rising sea level as consequences of increasing atmospheric concentrations of greenhouse gases. However, projections of the details about the magnitude, timing, and specific regional impacts and consequences are variable (IPCC, 2001a,b). The program is placing the highest priority on research aimed at addressing known modeling deficiencies (see Chapter 4, Question 4.1). The following objectives in pursuit of Goal 1 describe CCSP's long-term approach.

Objective 1.1: Accelerate research on climate forcing, responses, and feedbacks aimed at improving methods for quantifying and reducing uncertainties in the current generation of prediction and projection models

The climate system responds in complex ways to changes in forcing that may be natural (e.g., variations in the magnitude of solar radiation reaching the top of the atmosphere) or human-induced (e.g., changing atmospheric concentrations of greenhouse gases). Several of the program's science elements will provide climate modelers with the best scientific estimates of past and expected future climate forcing factors—for example, the Climate Variability and Change research element for solar variability; the Atmospheric Composition, Carbon Cycle, and Human Contributions and Responses research elements for radiatively active trace gases and aerosols; and the Land-Use/Land-Cover Change and Ecosystems research elements for land surface cover changes and energy exchanges.

The direct response of the climate to a change in forcing may be either diminished or amplified by feedback processes within the climate system itself. For example, warmer upper oceans will result in increased evaporation and, thus, increased concentrations of atmospheric water vapor—itself a strong greenhouse gas—a positive or amplifying feedback. Increased water vapor will alter cloudiness, which may be either a positive or a negative feedback, depending on the cloud height and type. Climate-induced changes at the land surface (e.g., through more intense and higher frequency droughts) may in turn feed back on the climate itself, for example, through changes in soil moisture, vegetation, radiative characteristics, and surface-atmosphere exchanges of water vapor.

Near-Term Priorities

- Because of the highly interdisciplinary and complex nature of climate processes in general, understanding and modeling feedbacks is a challenging research task. The program will give high priority to research conducted under the research elements aimed at understanding and modeling the most important known feedback processes (see Chapter 4, Question 4.1), with the goal of better quantifying and reducing uncertainties in climate predictions and projections.
- CCSP-supported climate modeling centers will work closely with scientists to use observations and research advances to improve modeling capability and provide more useful products for decision support. The knowledge transfer will be enabled and accelerated by **C**limate **P**rocess and Modeling **T**eams (CPTs), a new paradigm for CCSP climate modeling and applications research (CPTs are discussed later in this chapter and in Box 4-1).

Enhanced understanding and improved representation in models of the processes that influence climate will improve confidence in model forecasts and projections. Reductions in uncertainty will be measured by the degree to which differences between the major climate models as well as differences between observations and relevant model fields are reduced.

Objective 1.2: Develop the next generation of global climate models through the addition of more complete representations of coupled interactive atmospheric chemistry, terrestrial and marine ecosystems, biogeochemical cycling, and middle atmospheric processes

Past emphasis has been on the development and testing of physical aspects of coupled atmospheric and ocean general circulation models (GCMs). This occurred primarily because climate models have their roots in numerical weather prediction models (atmospheric GCMs with some ocean coupling that treat primarily physical processes), and the available observations were those derived for the application of weather prediction models. Significant advances have been achieved on the physical aspects of climate modeling, but much more research is required (see Chapter 4).

In the 1990s, motivated by unresolved questions about long-term climate change, modeling efforts expanded to include additional components of the climate system, such as chemistry and biology, that are important to longer term climate processes. Here too, much has been accomplished, but much remains to be done. In parallel with continued research into physical climate processes and modeling, the program will enhance efforts to more fully develop the chemical and biological components of climate models, including their human dimensions, in the context of a coupled interactive system, and also expand the atmospheric domain to include middle-atmosphere processes. This priority is motivated by the need to provide answers to pressing questions about long-term change and variability that may result from human-induced climate forcing involving chemical, biological, and human-induced processes.

Near-Term Priorities

- In the near term, work will concentrate on improved representations of aerosols, elements of the carbon cycle,

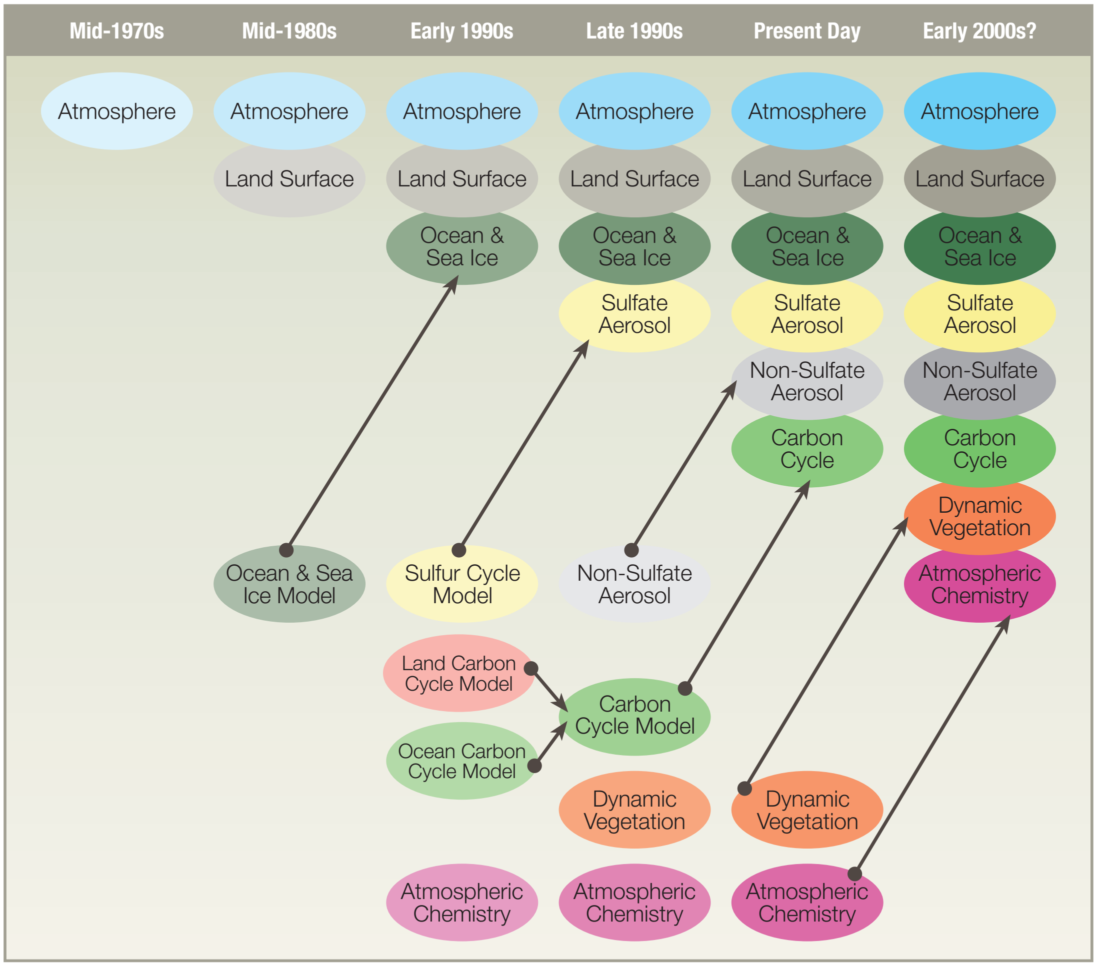


Figure 10-1: The development of climate models over the last 25 years showing how the different components are first developed separately and later coupled into comprehensive climate models. Source: IPCC (2001a).

interactive land surface-atmospheric processes, and middle-atmosphere dynamics and chemistry. This work will integrate research advances by the CCSP research elements (see Chapters 3-9). The products will be next-generation climate system models with enhanced capabilities to more comprehensively model the interactive physical, chemical, and biological components of the climate system. This work will continue over the longer term, leading to fully interactive Earth system models. For a more detailed description of research planned for one key next-generation climate system model, see the Community Climate System Model website, <http://www.ccsm.ucar.edu/management/sciplan2004-2008>.

The Role of the Middle Atmosphere in Climate

- The representation of the stratosphere will be improved in climate models, including feedbacks between stratospheric dynamics and stratospheric ozone, and between stratospheric dynamics and water vapor (see Chapter 4).
- CCSP will examine whether variations in solar irradiance can play a significant role in the natural variability of the climate system. Models will be developed that extend vertically through the mesosphere and include interactions between ultraviolet radiation, ozone chemistry, and atmospheric circulation and transports (see Chapters 3 and 4).

Interaction of Aerosols, Chemistry, Ecosystems, and Hydrology

- CCSP will develop the capability to model a fully interactive aerosol system within climate models, in order to examine the multi-faceted roles of aerosols in the climate system (see Chapters 3, 4 and 5).

Atmospheric Composition

- CCSP climate system models will be developed to include both tropospheric and stratospheric chemistry, chemical processes related to interactions at the Earth's surface, and interactions with hydrologic processes, in order to adequately represent the sources, sinks, and transformation processes of those molecules that are important for climate because of their ability to absorb and/or emit radiation and whose concentration and properties must be adequately simulated in climate models (see Chapter 3.)

Biogeochemistry and Ecosystems

- CCSP will develop the modeling tools and validation data sets for incorporating and assessing historical and future land use; the dynamics of managed forest, rangeland, agricultural, coastal, and ocean systems; and deliberate carbon sequestration activities (see Chapters 6-9).

High-Resolution Climate Model

- At present, there are two complementary approaches to modeling climate change and climate impacts at regional and sector scales. One approach uses a variety of "downscaling" techniques, ranging from nested mesoscale (regional scale) models to adaptable global grids (see Objective 1.6). The second approach is to increase the resolution of the global models themselves, throughout the entire global domain. The former approach is complicated by several unresolved issues, ranging from the effects of lateral boundary processes to conservation principles. The second approach is not practical without very large increases in computing capability. The CCSP strategy is to continue to support research in and applications of regional-scale climate models and other downscaling methods. On a smaller scale, the program will support pilot projects for next-generation very high-resolution global climate model development, in anticipation of continuing advances in computational technologies.

Climate models and observations are intimately connected, as described under Objectives 1.3-1.5 below. Models must be evaluated and constrained by observations, which also serve to initialize models used for prediction. Models provide a dynamically consistent framework into which diverse climate observations can be assimilated to produce "value-added" data sets of gridded, continuous time series of hybrid field observations and modeled data.

Objective 1.3: Foster model analysis and testing through model diagnostics and intercomparison activities, including comparison with observations

Given the complexity of climate models, it is difficult to ascertain why a particular model performs "better" or "worse" than others in any given situation. Generally speaking, a measure of a model's quality is its ability to simulate the current climate [global averages, annual cycle, major modes such as the El Niño-Southern Oscillation (ENSO) and North Atlantic Oscillation (NAO), etc.] and the climate of the past centuries (19th and 20th) as measured by available observations. Therefore, it is essential to carefully identify and document model deficiencies, such as systematic biases ("bias" refers to the tendency of a model's prediction to drift toward the model's climatology, which may be at variance with the real world). Furthermore, thorough diagnostics of model deficiencies (e.g., intercomparison of various models, comparison of models to observations, analysis of physical mechanisms using simplified or conceptual models, and carrying out model sensitivity experiments) are essential to identify sources of model errors, which then provide the basis for model improvement.

Near-Term Priorities

- Various projects aimed at fostering intercomparison among climate models or their components are underway. The program will continue to support these efforts in model intercomparisons, with an emphasis on the diagnostics for the sources of deficiencies common to many climate models, such as the "double Intertropical Convergence Zone (ITCZ)" problem in the tropical Pacific Ocean, which is closely associated with the modeling of tropical deep convection and cloud feedbacks. A key approach is to bring together the expertise and interests of observation specialists, process modelers, diagnosticians, and climate modeling centers to tackle the problem from various angles in a coordinated manner (e.g., the CPT approach).
- Given the status of observations, it is not obvious which model(s) are "better" (see Chapter 12, Goal 4). In practice, when assessing how models simulate the present climate, most of the comparisons are made using "reanalysis data" provided by one of several groups. A wealth of satellite data is already available, with much more coming available. The linkage between satellite data and the needs of modeling groups that has been made very effectively in some modeling organizations (e.g., NASA's Data Assimilation Office, NOAA's National Centers for Environmental Prediction) should be replicated by other CCSP modeling groups. The program will address the role of both the modeling groups and the remote-sensing teams (see Chapter 12, Goal 6). Those modeling groups that have not made use of satellite data in the past will be encouraged to utilize it as part of their activity. Remote-sensing projects will be better integrated into the modeling community, with the scientific research team associated with each instrument encouraged to provide user-friendly data sets for modeling as part of their data collection responsibility.
- For paleoclimate studies, there is often a large gap between the actual data being obtained and the interpretation of those data in terms of the climate variables output from each model. When there is an apparent mismatch between model output and climate interpretation, it is often unclear whether the interpretation of the paleoclimate proxy data is responsible. To minimize this problem, the program will encourage modelers to include direct representations of the paleoclimate proxy data (e.g., water isotopes), so that comparisons can then be made with the proxy data independent of any climate interpretation. This will also help to improve the value of proxy data.
- At times, model performance can look satisfactory when compared with one reanalysis data set, and less so compared with another. As in the case of GCM differences, the reasons for the reanalysis differences need to be better understood. The program will encourage improved understanding through close cooperation between the reanalysis modeling data centers and observational and empirical scientific research (e.g., via a CPT). This effort will require international cooperation, and possibly some joint funding of such comparisons through international entities, such as the World Meteorological Organization (see also Objective 1.5).

Some key examples of global climate model intercomparison projects include the Atmospheric Model Intercomparison Project (AMIP, <www-pcmdi.llnl.gov/amip/>), the Coupled Model Intercomparison Project (CMIP, <www-pcmdi.llnl.gov/cmip/>), and the Paleoclimate Model Intercomparison Project (PMIP, <www-lsce.cea.fr/pmip/>). AMIP was initiated in 1989, for the purpose of identifying and documenting the differences among the various atmospheric models and observations, to provide a basis for model improvement. Nearly all atmospheric models in use today have been calibrated using the AMIP experimental protocol. AMIP is closely integrated with CMIP, and provides a calibration for understanding how coupled models respond to increasing levels of greenhouse gases. Model-model and model-measurement intercomparisons have been carried out for a number of component models that will ultimately need to be incorporated into global climate models. For instance, multi-dimensional stratospheric composition models have been intercompared with both each other and with observations in a series of "Modeling and Measurement" papers.

CMIP, like AMIP, is an activity of the World Climate Research Programme (WCRP). It was initiated in 1995 with the goal of collecting and intercomparing simulations from global coupled climate models—that is, models that operate over the complete global three-dimensional domain of the climate system, with components typically consisting of atmosphere, ocean, sea ice, and land surface. Virtually every global coupled model group worldwide is participating in CMIP, including groups from Australia, Canada, China, France, Japan, Germany, South Korea, Russia, the United Kingdom, and the United States.

PMIP, launched in 1994 and endorsed by the International Geosphere-Biosphere Programme and WCRP, is an international project involving members of all the major modeling groups worldwide. The aims of the PMIP project are to improve understanding of the mechanisms of climate change by examining such changes in the past, and to evaluate the ability of climate models to reproduce paleoclimate conditions radically different from present-day climate.

Objective 1.4: Improve short-term climate predictions through model initialization with enhanced observational data

Over the past several decades, progress in improving numerical weather forecasting has been achieved primarily through the continuing increase in model resolution and improvement in initializing (specifying the values of the model's variables at the start of the forecast) the prediction models. Initialization has been improved through the increase in available observations, particularly from remote-sensing platforms, and by advances in data assimilation techniques.

Improving climate prediction can follow a similar path. Although seasonal climate forecasting using coupled climate models is still at an early stage of development, the most significant impact on forecasts in the past decade has come through the use of ocean data assimilation to assimilate *in situ* observations for initializing the coupled models for ENSO forecasts.

Near-Term Priorities

- To improve short-term climate forecasts, CCSP modeling will incorporate new and improved technologies in data assimilation, such as coupled ocean-atmosphere data assimilation and land data assimilation, and better utilization/assimilation of *in situ* and remotely sensed global oceanic, atmospheric, and terrestrial observations (e.g., better utilization of altimetric sea-level data and improved methodologies for assimilating soil moisture and sea surface salinity; see also Chapter 12).
- The most significant challenge in data assimilation for climate prediction is the bias in prediction models. To reduce model bias, CCSP will significantly improve physical formulations of climate models, through improved incorporation of existing and new observations as well as through results from new process studies.
- Observations of several new variables have been demonstrated to be critical for improving seasonal forecasts, including sea surface salinity (SSS), particularly in tropical oceans, and soil moisture over the land. Satellite missions for measuring SSS and soil moisture have been planned for the next decade (see Chapter 12). In conjunction with efforts to make these observations available globally, the program will invest in research and development on the use of salinity and soil moisture observations in data assimilation for initialization of climate forecast models.

Objective 1.5: Provide comprehensive observationally based model-assimilated climate data sets for climate process research and testing of climate model simulations and retrospective projections

There is a critical need for an ongoing effort to provide complete descriptions of the present and past state of the atmospheric and oceanic components of the global climate system, together with continually updated data sets compiled in consistent ways to enable comparison of models with observations (see Chapter 12). As new climate observations are obtained, it is essential to place them in a historical context to enable the accurate evaluation of departures from normal, and trends and change in variability. New observations can provide additional information about climate when they are put in the context of past observations at uniformly spaced points in space. This is accomplished through the systematic processing and integration of climate observations using the state-of-art climate models and data assimilation methods.

Near-Term Priority

- The program will support research and development of advanced data assimilation methods and the production of global climate time series to establish reliable climatologies, identify real versus fictitious trends, and develop techniques to minimize the effects of changing observing systems and model biases.

Objective 1.6: Accelerate the development of scientifically based predictive models to provide regional- and fine-scale climate and climate impacts information relevant for scientific research and decision support applications

Regional climate models (RCMs, also called mesoscale models) are used in conjunction with GCMs to provide "downscaling" of climate variables for regional-scale predictions or projections. RCMs operate on scales that could not be accessed directly in GCMs due to computational capability limitations. Thus, while global climate models will be approaching 100-km resolution in the foreseeable future, it is unlikely that in the near future they will reach the 10-km scale that regional models can simulate. RCMs represent the most prevalent current approach to dynamic downscaling. An alternative approach is statistical downscaling, for which the applicability to climate change is uncertain. Other dynamic approaches include stretched-grid GCMs, with uneven horizontal resolution, which can provide regional-scale resolution over certain domains.

RCMs can also be used for "upscaling" of information to test GCMs. To the extent that many small-scale processes, parameterized in general circulation models as "sub-grid scale," can be better simulated in regional models, they can provide feedback on the adequacy and limitations of the coarse-grid parameterization schemes.

While the finer resolution provided by regional-scale models is desirable, the quality of the resulting solutions is limited, except perhaps in better delineating orographic (mountain region) precipitation. There are several broad issues involved in the use of regional models. While such models may allow many physical processes to be incorporated on the scale at which they occur (e.g., rainfall in the vicinity of mountains), the physics on regional scales is often uncertain. The uncertainties have led to the existence of multiple versions of most RCMs. When utilizing them for climate change simulations, the different versions can produce results that differ from each other by as much as the observed climate changes they are attempting to simulate, which questions their use by policymakers and decisionmakers.

A second issue is consistency. Regional-scale models of necessity generally utilize physical parameterizations that differ from those of the GCM, if for no other reason than because parameterizations are often scale-dependent. The GCM supplies boundary conditions generated with one physics package, and the RCM utilizes these boundary conditions in conjunction with different physics. This effect is made worse in "two-way coupling," in which the mesoscale result is fed back to the GCM. Using a mesoscale model over the Rocky Mountains, for example, and not at the same time over the Himalayas, provides inconsistent forcing for the GCM planetary wave structure, which is affected by both mountain chains.

Near-Term Priorities

- Many challenging downscaling and upscaling research issues remain to be addressed in order to provide the most useful information possible for decision support. Although regional modeling is highly relevant to most of CCSP's participating agencies, research and applications are often centered on the missions and interests of individual agencies. This has resulted in a need for more focused leadership and coordination following the guidelines given in Chapter 16. Toward this end, CCSP will establish a process for coordination of regional modeling activities, including the development of methods to transfer regional decision support products into operations. Regional and sectoral climate and climate impacts research and modeling is a high program priority and its support will be accelerated.
- Reducing the uncertainty associated with such issues will require diagnostics and intercomparison of regional-scale models and application techniques. With CCSP support. regional models will be tested systematically when forced by real-world and GCM-produced boundary conditions, and the results quantified against regional observations for different locations. The different physical parameterizations being used on regional scales will be compared with observations when available, and assessments made of their realism. Regional reanalysis and observational data sets will be used for verification purposes when evaluating RCM output.
- To provide greater consistency and to help improve GCMs, CCSP will support upscaling of well-validated physics at the regional level to provide insight into parameterizations for the coarser grid GCM. For example, the mesoscale model resolution will be expanded systematically to learn how the results change, and help determine what is appropriate for GCMs. This approach is promising (e.g., for physically based cloud-resolving models).

Goal 2: Provide the infrastructure and capacity necessary to support a scientifically rigorous and responsive U.S. climate modeling activity.

The principal U.S. agencies that support climate model development and application commissioned NRC to analyze U.S. modeling efforts as well as to suggest ways that the agencies could further develop the U.S. program so that the need for state-of-the-art model products can be satisfied. The NRC reports, *The Capacity of U.S. Climate Modeling to Support Climate Change Assessment Activities* (NRC, 1999b) and *Improving the Effectiveness of U.S. Climate Modeling* (NRC, 2001d), provided valuable guidance on how to improve U.S. climate modeling efforts. Also, the U.S. Global Change Research Program issued *High-End Climate Science: Development of Modeling and Related Computing Capabilities* (USGCRP, 2000), a report commissioned by the Office of Science and Technology Policy to make recommendations on climate modeling activities.

These documents emphasized four key points: (1) the acknowledged U.S. leadership in basic climate research that generates the knowledge base, which underpins both domestic and international modeling programs; (2) the limited ability of the United States to rapidly integrate the basic climate research into a comprehensive climate modeling capability; (3) the challenges, including software, hardware, human resource, and management issues, to routinely produce comprehensive climate modeling products; and most important, (4) the need to establish a dedicated capability for comprehensive climate modeling activities, including the global climate observations and data that support modeling.

Objective 2.1: Provide the computing, data storage and retrieval, and software engineering resources required to support a world-class U.S. climate modeling activity

The production of global model predictions of climate variability and change with sufficient resolution and veracity to provide useful regional information to decisionmakers requires a comprehensive computational infrastructure of computing resources, data centers, networks, and people. The success of this enterprise is predicated on a long-term commitment of the program to sustain the institutional support and investment required to maintain a resilient and state-of-the-art computational and information technology infrastructure.

Near-Term Priority

- CCSP will support researchers in developing more comprehensive coupled models that need to be evaluated, then exercised to produce ensemble projections of multi-century climate change scenarios. The results from these runs will be analyzed and employed by hundreds of researchers engaged in climate studies, impacts research, and assessment.

High-end computing needs are often divided into the two broad and overlapping categories of *capability* needs and *capacity* needs. The former refers to applications that require the *capability* to do sophisticated, cutting-edge simulations that were impossible just a few years ago because the computing platforms to execute them did not exist. Typically, these simulations require the dedicated use of the most powerful computer available for several weeks at a time. Ensemble simulations with the current and next generations of coupled models fall into this category. In addition to capability resources, CCSP requires a large amount of *capacity* resources to carry out the bulk (in terms of total computing cycles) of its modeling and analysis needs.

Near-Term Priority

- To meet its mandate, CCSP will provide researchers at the major modeling centers with access to steadily growing computational resources that increase by a factor of four each year. This will result in a 256-fold increase in available computing power over 4 years and a roughly 1,000-fold increase over 5 years. The factor of 1,000 will provide a three-fold increase in resolution which corresponds to a factor of 20 increase in computing requirements, a factor of two for improved process representation, a factor of four for increased comprehensiveness, a factor of three for increased ensemble size, and a factor of two for an increased number of scenarios. This level of enhancement will meet the computational requirements for the next-generation climate system models (described in Objective 1.2). This will be accompanied by appropriately scaling investments in software engineering, input/output systems, and local storage systems together with increasing investments in high-end analysis and visualization software development. A part of the growth will be met as computing equipment is replaced periodically every 3 to 5 years, with better technology at lower prices (Moore's "law").

Currently, capability resources needs are met through a combination of dedicated and shared resources. The dedicated resources—particularly the computers at the NOAA, NASA, DOE, and NCAR laboratories—do not fully meet the needs of the modeling community. The shortfall is made up by additional resources acquired at several shared-access supercomputer centers by the researchers themselves, through individual proposals. These centers are not supported by CCSP and provide computing through a competitive review process among many researchers from many fields of science and engineering. CCSP objectives cannot be met without these additional computing resources.

One example of such computing resources is DOE's National Energy Research Scientific Computing (NERSC) facility at the Lawrence Berkeley National Laboratory. To help meet computing needs for U.S. climate modeling, 10% of the computing cycles at NERSC will be made available to the broader scientific community in an open competition, with a special emphasis on climate modeling. Those cycles that might be allocated for climate modeling in that open competition would supplement the cycles at NERSC already used for climate modeling.

Possible collaborations with the Earth Simulator center in Japan, which has a computer with 20-50 times the capability of any existing U.S. machine for climate model applications, may help meet some of the near future needs. Unfortunately, this resource is now not directly accessible to U.S.-based researchers, because its lack of appropriate communication and mass storage and retrieval capacity requires users to be physically located at the center. Data generated at the center must be transferred to storage media that are then physically transported to data archives in the United States. This problem may be resolved in the near future.

Near-Term Priority

- In April 2003, the Office of Science and Technology Policy initiated a High-End Computing Revitalization Task Force (HECRTF) to assess the current high-end computing capability and capacity within the federal agencies, and to develop a plan to revitalize high-end computing research and enable leading-edge scientific research using high-end computing. CCSP has been coordinating with HECRTF to ensure that the CCSP computing capability and capacity needs are considered.

The divergence in high-end computing architectures over the last decade has made developing models for high-end capability machines more labor-intensive, requiring the addition of a software engineering component to model development.

Near-Term Priority

- Recent CCSP projects, including the NASA Earth System Modeling Framework (ESMF) program (see Objective 3.2) and the DOE Community Climate System Model (CCSM) Software Engineering Consortium program address this requirement. CCSP will support their continuation.

In addition to these primary capability computational resources, CCSP requires a network of available capacity computing engines, data archives, and associated information technology infrastructure to make the model products readily available and accessible, so that further analysis and the development of secondary products, such as downscaled model information, can be used for research and assessment. While the current archive of model results totals several tens of terabytes (trillions of units of information), future model data archives, and associated observational data to evaluate the models, will consume tens of petabytes (thousand terabytes).

Near-Term Priority

- The information technology infrastructure will be tailored to meet the specific needs of the CCSP modeling community, which will require the development and maintenance of both the software and hardware components that form the backbone of the infrastructure. To accommodate the rapid rate of turnover in information technology, the infrastructure will be flexible and dynamic so that it can evolve over time to meet increasing demands and utilize the best available technology. Projects such as the DOE Earth System Grid (ESG) provide a start in this direction by cataloging and making a subset of the existing model archives available over the Internet, but far more is needed. Contingent on continued progress and merit of the ESG project, the DOE Office of Science will continue to directly support ESG through at least 2005.

Objective 2.2: Establish graduate, post-doctoral, and visiting scientist programs to cross-train new environmental scientists for multidisciplinary climate and climate impacts modeling research and applications

The development, testing, and application of climate system models requires environmental and computer technicians and scientists with expertise in a broad range of disciplines. The scientific disciplines include atmospheric physics and chemistry; ocean physics, chemistry, and biology; ice physics; biological ecology; geology; applied mathematics; and the interactions among them. The activity also requires computer software engineering to develop, test, and manage model code (which, for a state-of-the-art climate system model, is currently about 500,000 lines and is projected to grow to about one million lines over the next 5 years).

Near-Term Priority

- As climate modeling becomes ever more complex, a shortage of appropriately trained scientists and technicians has become one of the limiting factors to progress. To meet this need, CCSP will establish a graduate student, post-doctoral, and visiting scientist fellowship program for climate modeling research and applications. The program will offer cross-training opportunities in climate modeling and computer sciences/software engineering. A modest post-doctoral and visiting scientist program has been established in FY2003 and will be expanded in future years.

Goal 3: Coordinate and accelerate climate modeling activities and provide relevant decision support information on a timely basis.

The NRC review of U.S. climate modeling (NRC, 2001d) recommended the following as high priorities for the nation:

- Centralized operations and institutional arrangements for delivery of climate services
- A common modeling infrastructure
- Human resources.

The dispersed and diverse nature of climate research, including climate modeling research, in the United States requires an integrating strategy to rapidly infuse new knowledge into the most complete models used to simulate and predict future climate states. At the same time, the ability to provide decision support requires a robust and ready modeling capability to perform specialized projections and simulations to inform policymaking. A multi-tiered CCSP strategy has evolved over the last several years to address shortcomings identified in NRC reports on U.S. integrated climate modeling efforts (NRC 1999b, 2001d), as well as to meet anticipated future demands. The strategy combines a "bottom-up" approach required to solve difficult basic research problems with a "top-down" approach to focus a component of modeling research on the needs for decision support.

At the most fundamental level of the strategy is the large number of basic research projects at universities, federal laboratories, and in the private sector, which, along with the larger centers, produce new knowledge required to further improve climate models.

The middle level includes modeling centers that conduct essential research and development for climate, weather, and data assimilation applications. These centers are of two types, the first of which are the large modeling centers that develop and maintain state-of-the-science global models but have primary missions other than century-scale global climate projection, although they may have some activities in that area. These centers include the NOAA National Center for Environmental Prediction, which conducts operational weather and climate prediction; the NASA Goddard Institute for Space Studies, which focuses on using satellite data to provide representations of climate forcing fields and uses these to model and study climate sensitivity to natural and human forcings; the NASA Goddard Space Flight Center, which focuses on the use of satellite data to generate research-quality data sets, to improve climate models, and to improve weather and coupled model predictions; the International Research Institute for Climate Prediction, which prepares and internationally distributes seasonal-to-interannual climate prediction and impacts products; and the Center for Ocean-Land-Atmosphere Studies, which focuses on studies of the predictability of climate. The second type is a number of smaller centers that have focused research interests on specific questions in climate research.

The strategy includes, at its third level, two "high-end" climate modeling centers that will continue to develop, evaluate, maintain, and apply models capable of executing the most sophisticated simulations, such as those required for assessments by the Intergovernmental Panel on Climate Change (IPCC). These two centers—one based at the NOAA Geophysical Fluid Dynamics Laboratory (GFDL) and the other based on CCSM and coordinated by the National Center for Atmospheric Research (NCAR)—are complementary, cooperative, and collaborative. Both high-end modeling groups have a long legacy of successful climate change research that predates the IPCC process and have led U.S. participation in international modeling evaluations and assessments.

A healthy balance of resources (financial, human, and computer) among these three levels is essential to maintain a strong U.S. applied modeling program. Researchers collaborate extensively across all three tiers, ensuring the rapid flow of knowledge and understanding, as well as the definition of new problems. One example of such collaboration is support for a common modeling infrastructure (CMI) and the Earth System Modeling Framework to optimize modeling resources and enable meaningful knowledge transfer among modelers. By adopting common coding standards and system software, researchers will be able to test ideas at any of the several major modeling centers and the centers themselves will be better able to exchange model components.

The multi-tiered strategy provides a structure by which the diverse contributions of the basic research community can be quickly utilized and integrated in state-of-the-art models used for climate simulation and prediction. At the same time, the strategy supports the decision support requirements of CCSP to make model simulations available for policy and impacts studies.

Objective 3.1: Provide routine, on-demand state-of-the-science model-based global projections of future climate

A major CCSP objective is to develop scientifically based global, time-dependent, multi-century projections of future climate change for different scenarios of climate forcing caused by natural variations and human activities. These projections are a primary form of scientific information to support decisionmaking about options to address the potential consequences of climate change. Development of capabilities to produce world-class climate change projections on demand to meet the needs of international and national assessments and other decision support requirements will bring new cohesion and coherence to the efforts of the U.S. climate modeling community. Given current scientific uncertainty and gaps in knowledge, it is essential that the United States maintain more than one high-end modeling center focused on long-term climate change, so that differing approaches to unsolved problems can be explored.

Both CCSM and GFDL support ongoing development of comprehensive climate system models, involving chemistry, biogeochemistry, and ecological processes. The centers are engaged in the development and application of distinct models. Their methods, innovations, and working hypotheses differ regarding many of the outstanding unresolved theoretical and modeling issues. The different approaches are essential at this stage, given the highly complex nature of the climate system with its numerous feedback mechanisms across a broad range of temporal and spatial scales.

Further, a comprehensive U.S. climate modeling strategy benefits from a measure of differentiation between the roles of the two centers. Despite an apparent overlap in responsibilities, the missions and structures of the two centers are more complementary than duplicative. CCSM is an open and accessible modeling system that integrates basic knowledge from the broad, multidisciplinary basic research community for research and applications. The GFDL model development team participates in these community interactions and will focus on model product generation for research, assessments, and policy applications as its principal activity. GFDL models and products are integral to the development of the NOAA Climate Services program, which provides operational climate products and services to policymakers and resource managers. GFDL maintains dedicated computer resources that can be allocated flexibly to meet mission requirements.

Near-Term Priorities

- Results from GFDL and CCSM models will comprise the primary U.S. contributions to IPCC assessments, as well as provide input to other assessments of the science and impacts of climate change. Independent century-long climate projections will be executed by each center on schedules to meet national and international assessment demands.
- CCSM will maintain an open model development system with major changes developed through consensus from the broad scientific community engaged in climate research. Computer resources for CCSM research will continue to be provided mostly at shared-access supercomputer centers through allocations given to the many projects associated with CCSM. This arrangement works well for the IPCC and other major assessments that have long lead-times that allow for sufficient planning.
- GFDL plans to procure additional supercomputing resources to enable the systematic generation of model products needed by the impacts, assessments, and policy communities to document and assess the regional and global impacts of long-term climate variability and change. In addition to products derived from GFDL model simulations, additional products will be generated using results from other modeling centers, including CCSM.
- Although they will maintain separate model development paths, the two centers have developed, and will implement, a plan for extensive scientific interaction and collaboration. The first step is to understand why the two coupled models have significantly different climate sensitivity to increased atmospheric carbon dioxide concentrations. Initial studies indicate that the prediction of changes in cloud amount in response to atmospheric warming is very different in the two models (see Figure 10-2). This suggests that an important factor leading to differences in climate sensitivity is the differences in representation of cloud processes.
- The centers will work with the broader scientific community of university and other laboratory modeling groups to focus research, including climate process studies, to better understand and resolve the differences between the models.
- Further enhancement of the collaborations will be enabled by the following actions, some of which are dependent upon sufficient resources: a program of focused model intercomparisons (see also Objective 1.3); a graduate student, post-doctoral, and visitors program to accelerate interactions (see also Objective 2.2); and development of common model diagnostics.
- The centers will work cooperatively to develop methods for providing global model output for a variety of decision processes (see Chapter 11).

Objective 3.2: Develop mechanisms for effective collaborations and knowledge transfer

Climate Process and Modeling Teams. Climate scientists who conduct observational and empirical research into climate processes are often not well connected with modeling centers and model

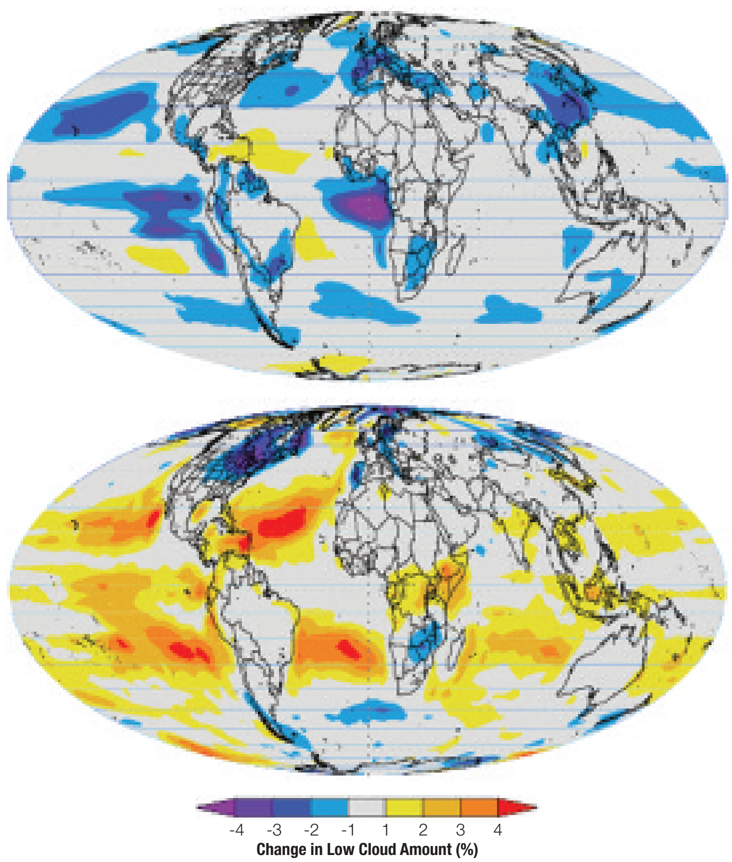


Figure 10-2: Changes in the amount of low clouds simulated by the GFDL model (top) and CCSM (bottom) resulting from a doubling of atmospheric carbon dioxide concentration. In many areas, the amount of low cloud is reduced in the GFDL model, where the amount of clouds increases over most areas in CCSM. This difference in behavior may be a major source of the models' differing climate sensitivities. Source: GFDL and NCAR.

developers. The U.S. Climate Variability and Predictability (CLIVAR) program has developed and promoted a research strategy that involves the formation of **C**limate **P**rocess and Modeling **T**eams in order to improve collaboration between researchers and modelers. CPTs consist of process-oriented observation specialists, researchers, and individual process and parameterization modelers, working collaboratively with climate model developers. The teams are organized around an issue, model deficiency, and/or parameterization(s) that are generic to all climate models. An important distinction between CPTs and other more conventional model development research is the emphasis on directed teamwork, demonstrated progress, and delivery of products that will be tested and possibly implemented in climate models.

Near-Term Priority

- The goal of the CPT approach is to facilitate and accelerate progress in improving the fidelity of climate models and their predictions and projections. Specifically, CPTs will:
  - Speed the transfer of theoretical and practical process-model understanding into improved treatment of processes in climate system models (e.g., coupled models and their component models, assimilation and prediction systems), and demonstrate, via testing and diagnostics, the impact of these improvements
  - Identify process study activities necessary to further refine climate model fidelity
  - Develop observational requirements for climate system models.

  Success of CPTs will be measured not only by advances in knowledge, but more importantly by the development of new modeling capabilities and products. Several pilot-scale CPTs are being funded by CCSP in FY2003 (see Chapter 4).

Common Modeling Infrastructure and Earth System Modeling Framework. One of the great strengths of atmospheric, oceanic, and climate modeling in the United States is the variety, availability, and wide use of models. But this diversity has also led to duplication of effort and a proliferation of models and codes that, due largely to technical reasons, cannot interoperate and have been unable to keep up with and exploit advances in computing technology.

Climate models are increasingly being used to support decisionmaking. The predictive requirements are becoming more stringent. The demand for interoperability of climate model components has intensified as various modeling groups are engaging in collaborative research. Without exchangeable model components, it is often difficult to point to a component as a clearly identifiable cause of divergent results when one model is compared against another or against observations. In order to optimize modeling resources and enable meaningful collaborations among modelers, it is necessary to build common and flexible modeling infrastructure at the major centers.

The common modeling infrastructure that will be implemented by the two centers will enable the exchange of model components between different modeling systems and facilitate analyses and intercomparisons of model results by adopting common coding standards for model components and common output formats, and developing common diagnostics packages. To achieve part of this commonality, the Earth System Modeling Framework project has been established. ESMF is a community-wide engineering effort to develop common software to facilitate interoperability of climate models on various hardware platforms, especially on massively parallel architecture platforms (i.e., many individual computational units operating in parallel, connected by data communication links).

Near-Term Priority

- CCSP will support further development of CMI/ESMF through multi-agency mechanisms that will ensure participation of the major U.S. climate modeling centers and groups. CMI/ESMF will: (1) facilitate the exchange of scientific codes (interoperability) so that researchers may more readily interface with smaller scale, process-modeling efforts and can share experience among diverse large-scale modeling efforts; (2) promote the implementation of standard, low-level software, the development of which now accounts for a substantial fraction of the software development budgets in many institutions; (3) focus community resources to deal with changes in computer architecture; (4) present the computer industry and computer scientists with a unified, well-defined, and well-documented task to address; (5) share the overhead costs of software development, such as platform-specific user libraries and documentation; and (6) provide greater institutional continuity to model development efforts by distributing support for modeling infrastructure throughout the community. Products will include more efficient and rapid transfer of research results into model applications, and human resources and dollar cost savings.

Objective 3.3: Provide for interagency coordination of CCSP modeling activities to improve implementation and external advisory processes to evaluate performance

Near-Term Priorities

- CCSP modeling activities are carried out by a number of agencies. In order to improve the coordination of the implementation of these activities at the program level, CCSP will establish a process for coordination of CCSP modeling activities that lie beyond the boundaries of the missions or programs of single agencies, including coordination of the use of computer resources that can be shared between agencies.
- CCSP will use advisory processes to facilitate its programs (see Chapter 16). In the case of its modeling strategy, CCSP will use a variety of advisory mechanisms to evaluate, guide, and provide feedback. Such mechanisms will include a continuing NRC relationship to examine strategic issues for future development, standing advisory committees, focused ad hoc working groups on technical issues (e.g., ESMF), and specialist workshops.

CHAPTER 10 AUTHORS

Lead Authors
David Bader, DOE
Jay Fein, NSF
Ming Ji, NOAA
Tsengdar Lee, NASA
Stephen Meacham, NSF
David Rind, NASA

Contributors
Randall Dole, NOAA
David Goodrich, NOAA
James Hack, NCAR
Isaac Held, NOAA
Jeff Kiehl, NCAR
Chet Koblinsky, NASA and CCSPO
Ants Leetmaa, NOAA
Rick Piltz, CCSPO