Community
Climate System Model Plan
(2000-2005)

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Preface

It is a pleasure to introduce the Community Climate System Model Plan (2000-2005). The evolution of the NCAR Community Climate Model (CCM) from an atmosphere only model in 1981 to the Climate System Model (CSM) in 1994 and now to the Community Climate System Model (CCSM) in 2000 has been quite remarkable. The CSM was the first coupled ocean–atmosphere model to be integrated for many years with no appreciable surface climate drift. The CCSM now contains fully interacting component models of the atmosphere, oceans, land, and sea ice, and work is well under way to include interactive biogeochemical, ecological, and chemical processes in the entire system. Parallel and coordinated efforts are under way to couple the neutral atmosphere with the thermosphere, an effort that will produce a scientific tool powerful enough to investigate quantitatively solar influences on tropospheric climate, a dream of UCAR and NCAR's father, Walter Orr Roberts.

Almost as impressive as the progress made in coupling the physical, chemical, and biological components of the earth system is the progress in getting many smart and independent people from different disciplines and institutions to work together to develop and use a true community model. Like the weather, everybody talks about the need for cooperation, partnerships, strategic alliances, and interdisciplinary research, but few actually do anything about them, at least at the scale of the CCSM. I congratulate the people who have worked together to bring the CCSM this far and encourage them to continue to work together to solve the immense challenges that lie ahead. These challenges include a myriad of scientific ones of solving tough problems in various components of the climate system (such as cloud-radiation interactions) and in coupling all of the components, many of which operate on vastly different temporal and spatial scales. The challenges are equally computational—how to achieve the massive increases in sustained computer performance needed to run ensembles of simulations at high resolution for a large variety of scientific and assessment purposes. The social challenge presented by the need for a very large number of scientists and policy makers from quite different disciplines, backgrounds, and cultures to work together in a sustained and harmonious manner cannot be overemphasized. I commend and thank a large number of people from our community who have contributed towards the success of the CCSM. And finally, adequate resources must be assigned to this effort in order to support the human resources and the infrastructure necessary to make the requisite progress on this critically important global, national, regional, and local problem. As we move toward a complete Earth System Model, we appreciate more than ever before the many dimensions of this "grand challenge" problem.

Rick Anthes
President of UCAR

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I. **The Climate System Model**

The Community Climate Model (CCM) was inaugurated in 1983 as a freely available global atmosphere model, developed at NCAR by NCAR scientists in collaboration with several scientists from the university and laboratory community, for use by the wider climate research community. A key benefit of such a community model is that climate scientists at many institutions do not have to develop models of their own to do their research. Instead, they can use a well-documented model that has been subjected to scientific scrutiny by many scientists for years. Over the past 16 years, this benefit has been increasingly realized as the formulation of the CCM has steadily improved and as computers powerful enough to run the model have become more widely available.

A limitation of the original CCM was that it did not include models of the global ocean and sea ice. Accordingly, in 1994, NCAR scientists submitted a plan to NSF to develop and use a Climate System Model (CSM) that was to include models of the atmosphere, land surface, ocean, and sea ice. These components were to be coupled without resorting to any "flux adjustments." The plan was to focus initially on the physical aspects of the climate system, and then in a subsequent version to improve biogeochemistry and coupling to the upper atmosphere. The first phase of this project was the model development by the NCAR staff, after which the model and associated data sets were to be made available to the scientific community. In addition, a new governance structure was promised, in which the interested scientific community would be given a fair opportunity to participate in all aspects of the CSM. NSF approved the plan, and model development began immediately.

In May 1996, the first CSM Workshop was held in Breckenridge, Colorado. At this workshop, the CSM components and the results of an early equilibrium climate simulation were presented. Working groups began to form, and the nature of future CSM governance was discussed. At the final plenary session of the workshop, the proposed management structure was discussed, modified, and adopted. At that point, the second phase of CSM, including full participation of the scientific community, had begun.

The period since this 1996 workshop has been a time of substantial organizational progress. A Scientific Steering Committee (SSC) has been formed to lead the CSM activity, working groups have been producing useful output, and the previously existing Climate Modeling, Analysis and Prediction (CMAP) Advisory Council has been reorganized as the CSM Advisory Board (CAB). (See Appendix A for the charges to the SSC and the CAB and the present makeup of these groups and the working groups.) In addition to support from NSF, interest in the CSM from other agencies, notably the Department of Energy (DOE) and NASA, has developed. As we work toward the second version of CSM, we believe that it is also time to recognize the community of users and sponsors by changing the name of the model to the Community Climate System Model (CCSM).

The period since May 1996 has also seen substantial scientific progress (described in detail in Section II). A 300-year run has been performed using the CSM, and results from this experiment have appeared in a special issue of the *Journal of Climate*, **11**, June, 1998. A 125-year experiment has been carried out in which carbon dioxide was prescribed to increase at 1% per year from its present concentration to approximately three times its present concentration. More recently, the Climate of the 20th Century experiment was run, with carbon dioxide and other greenhouse gases and sulfate aerosols prescribed to evolve according to our best knowledge from 1870 to the present. Three scenarios for the 21st century were developed: a "business as usual" experiment, in which greenhouse gases are assumed to increase with no economic constraints; an experiment using the Intergovernmental Panel on Climate Change (IPCC) Scenario A1; and a "policy-limited" experiment, in which emissions are assumed to be constrained, so that the concentration of carbon dioxide levels off at 550 parts per million by volume (ppmv) shortly after 2100.

During the past three years, shortcomings of the first version of CSM have become apparent. Furthermore, new components of the model have been, or are being, developed. This document describes the current state of the CSM effort and where the project is going over the next five years, including our plans for both model development and numerical experimentation.

Changes in climate, whether anthropogenic or natural, involve a complex interplay of physical, chemical, and biological processes of the atmosphere, ocean, and land surface. As climate system research seeks to explain the behavior of climate time scales of years to millennia, the focus necessarily turns to the interactions among the physical, chemical, and biogeochemical subsystems. The paleoclimate record reveals large correlated changes in atmospheric and oceanic circulation and biogeochemistry. The challenges of modeling the roles of anthropogenic emissions of carbon dioxide, reactive trace gases, and of changing land use in the earth system require a coupled-climate-system approach. While an appreciation that land-ocean-atmosphere interactions influence climate is not new, the emergence of coupled-climate-system questions as central scientific concerns of geophysics constitutes a major change in the research agendas of atmospheric science, oceanography, ecology, and hydrology.

Development of a comprehensive CCSM that accurately represents the principal components of the climate system and their couplings requires both wide intellectual participation and computing capabilities beyond those available to most U.S. institutions. The CCSM, therefore, must include an improved framework for coupling existing and future component models developed at multiple institutions, to permit rapid exploration of alternate formulations. This framework must be amenable to components of varying complexity and at varying resolutions, in accordance with a balance of scientific needs and resource demands. In particular, the CCSM must accommodate an active program of simulations and evaluations, using an evolving model to address scientific issues and problems of national and international policy interest.

The CCSM project will address important areas of climate system research. In particular, it is aimed at understanding and predicting the climate system. The long-term goals of the CCSM project are simple but ambitious. They are:

- to develop and to work continually to improve a comprehensive CCSM that is at the forefront of international efforts in modeling the climate system, including the best possible component models coupled together in a balanced, harmonious modeling framework;
- to make the model readily available to, and usable by, the climate research community, and to actively engage the community in the ongoing process of model development;
- to use the CCSM to address important scientific questions about the climate system, including global change and interdecadal and interannual variability; and
- to use appropriate versions of the CCSM for calculations in support of national and international policy decisions.

Complementary efforts using simplified models are also important and will be undertaken by many individuals, including some CCSM participants. However, the CCSM project will remain focused on comprehensive climate modeling.

We anticipate many important changes in the climate modeling enterprise over the next five years, including:

- increasing computer power, both in the U.S. and abroad, that can support more elaborate and more sophisticated models and modeling studies, using increased spatial resolution and covering longer intervals of simulated time;
- improved understanding of many of the component processes represented in the CCSM, including cloud physics; radiative transfer; atmospheric chemistry, including aerosol chemistry, boundary-layer processes, polar processes, and biogeochemical processes; and the interactions of gravity waves with the large-scale circulation of the atmosphere;
- improved understanding of how these component processes interact;
- improved numerical methods for the simulation of geophysical fluid dynamics; and
- improved observations of the atmosphere, including major advances in satellite observations.

The CCSM will evolve as these changes occur. This document summarizes our present view of how this evolution will proceed. It will be necessary to update this document at regular intervals, as our understanding improves.

II. Achievements and Accomplishments

A. Initial Development of the Climate System Model

Two years of intensive development of the component models for atmosphere, ocean, land, and sea ice, together with the coupling framework, culminated in the release of the initial version of the Climate System Model (CSM-1) in July 1996. This version included atmosphere and ocean general circulation models, a sea-ice model, and the coupler. The land model was embedded in the atmosphere model. In addition, a tropical Pacific Ocean model was included. For each component, a simple data model was also included to read existing data files instead of running the full component model.

The flexible nature of the modeling system was exploited to spin up the component models to produce compatible initial conditions for all components before coupling. The atmosphere was forced for several years with climatological sea surface temperatures (SSTs) and the results stored. The atmospheric results were then used to force the ocean and sea-ice models for several decades. The deep-ocean acceleration technique was used to get an effective deep-ocean spin-up of 500 years.

B. 300-Year Fully Coupled Control Simulation

The fully coupled model was integrated for 300 years. In this simulation, the global annual mean surface temperature exhibits an adjustment of 0.7 K over the first 5 to 10 years of the simulation and is remarkably stable afterwards. Figure 1 shows 12-month running means of surface temperature globally averaged over all surfaces. The mean of each series from years 11 to 300 is indicated by the horizontal line. The initial adjustment is largely due to a decrease of 1.5 K in the land temperatures, which occurred because a generic initial condition was inadvertently used in the Land Surface Model version 1 (LSM 1) instead of the equilibrated state from the end of the Community Climate Model version 3 (CCM3)/LSM 1 simulation. The ocean temperatures change rapidly in the first few months of the simulation, with the initial month being approximately 0.2 K warmer than any subsequent month. The coupled simulation varies strongly on multiyear time scales, but there are no surface temperature trends after year 10. The trends in land and ocean/sea-ice temperatures, determined by least squares fits for years 11 to 299, are 0.03 K per century, which is small compared to the standard deviations of the annual means of 0.2 K and 0.07 K, respectively, for these quantities. Over much of the globe, the annual mean simulated SSTs are similar to the observed SSTs, with errors of less than 1 K. The marine stratus regions off the western coasts of North and South America and off Africa are too warm by 2 to 3 K because of a bias in cloud simulation in CCM3. In higher northern latitudes, a shift in the Gulf Stream is apparent with a warm bias off Labrador, and the SSTs are too cold near Norway and in the North Pacific. These biases are accompanied by shifts in the ice distribution. The high-latitude southern ocean is slightly too warm, although the largest difference from the climatology is associated with deviations of the flow over large ridges in bottom topography.

The area covered by sea ice in the Northern Hemisphere increases for the first 20 years of the coupled simulation and then stabilizes with about 15% more sea-ice area than observed. The

excess is somewhat larger in winter than in summer. In the 80-year period from years 110 to 190, the winter sea-ice areas increase, and then they return to the earlier, somewhat too large value. The increased winter sea ice in the 80-year period is quite thin and does not have a clear signal in the total sea-ice volume.

The maximum sea-ice areas in the Southern Hemisphere drop to the observed level almost immediately in the coupled simulation, giving an annual cycle of sea-ice area that matches observations and remains stable throughout. The sea ice retreats back to the Antarctic coast in summer, while extensive regions of relatively thin, noncompact sea ice are found in winter, in agreement with observations.

C. Simulation of Transient CO_2 Increase

A coupled simulation in which the atmospheric carbon dioxide (CO_2) concentration increased by 1% per year was performed in collaboration with scientists from Japan's Central Research Institute of Electric Power Industry (CRIEPI). This simulation used initial conditions from year 15 of the 300-year control run. The CO_2 concentration was held fixed at 355 ppmv for 10 years, while instantaneous data was output every 6 hours. CO_2 was then increased at 1% per year for 115 years, at which time the concentration had increased by a factor of slightly more than three. Output was again obtained every 6 hours for 10 years beginning at the time of CO_2 doubling. The 6-hour output is being used by CRIEPI scientists as boundary and forcing data for regional model simulations. The globally averaged temperature increases by 1.25 K at the time of CO_2 doubling and 2 K at the time of CO_2 tripling, consistent with a 2 K equilibrium temperature increase simulated by the CCM3 coupled to a slab ocean. Figure 2 shows the 12-month running means of globally averaged surface temperature for the control simulation (blue) and the increasing CO_2 experiment (red).

D. Simulation of the 20th Century Climate

The Chemistry and Climate Change Working Group completed the first CSM simulation of the 20th century climate. A new spin-up and a short (40-year) control simulation of the coupled system were performed for 1870 conditions. A transient forcing simulation was then performed using reconstructions of atmospheric concentrations of sulfate aerosol, CO_2, ozone (O_3), methane (CH_4), nitrous oxide (N_2O), and chlorofluorocarbons CFC11 and CFC12. The latter four gases were advected in the CSM, and CFC11 concentrations were scaled to account for the effects of other halocarbons. The globally averaged temperature increased by about 0.6 K between the late 19th century and the 1990s, with most of the increase occurring since 1970, in agreement with observations. Figure 3 shows the globally averaged surface air (2 m) temperature anomalies (dark blue) with respect to the 170-year control simulation (black). Also shown is the observed global temperature record since 1860 (green). The CSM simulation showed levels of variability that compare well to the observed record prior to 1920, but it did not capture the observed maximum in the 1940s, which is believed possibly to have been caused, in part, by increased solar irradiance.

The effect of the simulated global temperature increase after 1970 can be clearly seen in the evaporation and precipitation, which also increased after 1970. The effect on the runoff rates was less clear. Although global runoff increased at the end of the simulation, it was not outside the range of variability found earlier in the simulation, before the temperature and precipitation increased significantly. There was some evidence of increasing snow accumulation in Antarctica and increased runoff in a few basins, but other basins showed no significant change.

E. 21st Century Climate Scenarios

The priority of 21st century climate scenarios was greatly increased late in fiscal year 1998 (FY98) to respond to requests for scenarios for the U.S. National Climate Assessment. The 20th century simulation described above served as a realistic initial condition for 21st century simulations. Specifications were completed for two forcing scenarios that used the same gases as in the 20th century simulations. Consistent trace gas concentrations and sulfur dioxide emissions were given for a "business as usual" and for a plausible policy-limited emissions scenario. Since the geographic distributions of anthropogenic sulfur dioxide emissions are expected to change with time, the aerosol model was solved interactively in these scenarios. The coupled model was tested and the scenario simulations were started at the end of FY98. Figure 4 shows the globally averaged surface temperature anomalies (dark blue) with respect to the 170-year control simulation, a 40-year segment of which is shown (black). Also shown are the observed global temperature record since 1860 (magenta), the globally averaged surface temperatures from the "business as usual" scenario (red), and the limited emissions scenario (green). The "business as usual" scenario shows an increase of 1.8 K in the average surface temperature over the 21st century. The rate of temperature increase decreases after 2050 in the limited emissions scenario, and the average surface temperature increases by 1.4 K over the 21st century.

F. CSM Development

The third major configuration of the CSM (CSM-1.2) was released in July 1998. Both active and data models are available for each of the components (atmosphere, ocean, land, and sea ice). Standard resolutions are T31 and T42 for the atmosphere and land components and nominal resolutions of 3 degrees and 2 degrees for the sea-ice and ocean components, respectively. Other resolutions are also possible. CSM-1.2 implements the same numerical algorithms as the previous versions of the CSM, with many improvements for more ease of use and portability. The land model is now a separate executable (no longer contained within the atmospheric executable), and it outputs independent netCDF files. The ocean model (NCAR CSM Ocean Model, NCOM-1.4) also outputs netCDF files, leaving the atmosphere model as the only component still using a private data format. We retained that format so that the atmosphere model will run efficiently on computers with relatively small memories (such as the Cray C90).

This distribution of the code is meant to be compiled and run on a Cray computer at NCAR. These restrictions are due to issues involving access to data files and linking to libraries. With some modest additional effort, these issues can be resolved. For example, this code has been adapted to run on Cray computers outside of NCAR and on both Silicon Graphics Inc. (SGI) and Nippon Electric Co. (NEC) machines. We anticipate that the next release of the code will be considerably more portable than the present code.

A new feature of the CSM-1.2's land component is a catchment basin runoff model, developed in collaboration with Jay Famiglietti (University of Texas at Austin). Runoff from the land model is routed to 19 catchment basins. Each land cell can drain into at most four basins determined from a 1/2 degree basin mask and wet surfaces (irrigated croplands, lakes, swamps, and glacial ice) and are assumed to be mass balanced. Testing of the incorporation of runoff into the coupled model is showing promising results, especially in terms of salinity trends in the ocean interior.

Several new features were developed for the CSM over the past year, and some were incorporated in the simulations of the 20th and 21st century climate discussed above.

- Philip Rasch (Climate Modeling Section or CMS) and Jan Egill Kristjansson (University of Oslo) incorporated the prognostic cloud water parameterization into the coupled simulations.

- Jeffrey Kiehl and Timothy Schneider (both of CMS) tested several alternative formulations for the (indirect) effect of aerosols on the cloud-drop size distribution and performed multiyear uncoupled simulations. However, the indirect effects are highly uncertain, and they are currently being omitted from transient climate scenarios. In addition, the direct effect of sulfate aerosols was included in the radiative transfer model.

- Sulfate aerosol distributions were obtained from the interactive sulfate chemistry model of Mary Barth (NCAR Atmospheric Chemistry Division), Philip Rasch and Jeffrey Kiehl (both of CMS). Three-dimensional aerosol distributions can be either specified from previous simulations or solved for interactively in the coupled model.

- Finally, the concentrations of CH_4, N_2O, CFC11, and CFC12 (the principal greenhouse gases except CO_2) were calculated in the model. The surface concentrations (not emissions) of these gases were specified, and loss frequencies were applied. They were derived from the photochemical model of Susan Solomon and Robert Portmann (NOAA Aeronomy Laboratory). Byron Boville, Lawrence Buja, Mariana Vertenstein, and

Brian Eaton (all of CMS) configured and tested the CSM with all of these features.

John Weatherly (Department of the Army Cold Regions Research and Engineering Laboratory or CRREL) found that the aerodynamic roughness length of sea ice used in the original CSM simulations (40 mm) was unrealistically large. As a result, we tested the model's sensitivity to using a smaller value (0.5 mm) that is appropriate for relatively smooth first-year sea ice. Note that the drag coefficient depends on the logarithm of the roughness length, so this change corresponds to a factor of four change in the surface stress over sea ice. The change had a modest impact on the ice distribution in either hemisphere. However, it significantly reduced the rate of Antarctic deep-water formation, which remains too large but is now closer to that in the real ocean. In consequence, the drift in deep-ocean salinity was reduced by an order of magnitude, and the drift in deep-ocean temperatures was reduced by a lesser amount. The smaller value is now used in all CSM simulations. Figure 5 shows the deep-ocean temperature and salinity as a function of time during the spin-up and coupled phases of the original 300-year coupled run with an aerodynamic roughness length for sea ice of 40 mm (black curves) and for a new 25-year coupled run with a drag coefficient of 0.5 mm (red curves). The initial values are realistic for these fields.

William Large (Oceanography Section or OS), James McWilliams (University of California at Los Angeles and OS), Gokhan Danabasoglu (OS), and Frank Bryan (OS) improved the tropical simulation of the ocean model significantly by reducing the vertical diffusion and incorporating an anisotropic horizontal viscosity tensor with greatly reduced cross flow diffusion. These changes resulted in a greatly improved simulation of the equatorial undercurrent in the Pacific and also of the surface countercurrents. Figure 6 shows the equatorial Pacific simulation, at 140ºW, from the original CSM ocean component (top) and the revised ocean model (bottom). A realistic value for the undercurrent is about 1 m/s, as in the new model. The meridional resolution of the ocean model was also increased to 0.6 degrees between 10ºS and 10ºN, but this had a much smaller impact on the simulation.

G. Fully Coupled Paleoclimate Simulations with the Low-Resolution CSM

The Paleoclimate Model Working Group completed two multihundred year, fully-coupled simulations with an augmented version of CSM-1.2 with T31 resolution in CCM 3.6 and the modified 3 degree version of the CSM ocean model. This ocean model has enhanced latitudinal resolution of 0.9° from 10°S to 10°N and 1.8° at middle and high latitudes and includes the anisotropic viscosity formulation developed by the NCAR Oceanography Section. New spin ups and multicentury simulations of the coupled system were performed for pre-industrial conditions (400-year run) and 1990 (200-year run). Trends in the volume mean ocean potential temperatures are small: -0.06°C/century in the pre-industrial run and 0.003°C/century in the 1990 run. This version of the CSM better resolves features of the present-day ocean. The equatorial undercurrent at 140°W has zonal velocities of 80 cm/s and a realistic width, compared to a much weaker (8 cm/s) and broader undercurrent in a previous simulation with the 3 degree resolution and isotropic viscosities. Interannual variability of tropical Pacific SSTs is also better defined in these new simulations with increased variability in the central and eastern Pacific. The model Niño3 standard deviation is 0.67°C, which is comparable to observed values for 1950–1979 of 0.70°C with enhanced power at periods of 3 to 4 years. The first empirical orthogonal function (EOF) of the model SSTs shows the familiar El Niño pattern with large positive values in the central and eastern tropical Pacific and the opposite sign in the north and south Pacific. Figure 7 shows the Niño3 and Niño4 SST anomalies and the first EOF pattern of tropical Pacific SSTs for a fifty-year period in a pre-industrial coupled simulation. Atmospheric modes, such as the Arctic Oscillation and North Atlantic Oscillation, are also reproduced realistically, as is their expression on northern continental climates.

III. Science Plan

Significant inadequacies have been identified in the original version of the CSM. Among these are:

- weaker than observed variability in the tropical atmosphere, especially that related to convection;
- poor simulation of marine stratus;
- incorrect seasonal behavior of the intertropical convergence zone;
- weak tropical ocean currents and variability;
- significant temperature biases in land surface temperatures in some regions; and
- excessive sea ice, in both spatial extent and thickness.

Improvements in all of the model components are required. CCSM working groups have developed plans for addressing these and other issues. In the four years since the CSM was released to the community, significant scientific progress has been made as discussed in Section II. For example, improvements have occurred in the simulation of the tropical ocean.

CSM-1 was developed internally at NCAR and optimized for vector supercomputers, which are not available to the U.S. modeling community at present. A significant amount of the CSM codes needs to be changed to work on the new distributed-shared-memory machines that are becoming available. The original model was developed before a significant CSM community existed outside NCAR. Although a small, internal group has been able to work efficiently on code development, a more robust, professional set of standards and procedures is necessary so that a larger, distributed group of people can work efficiently on the CCSM.

Working group members are planning to develop the CCSM to take advantage of these opportunities. The plan described below concerns model development and improvements and new activities.

A. Goals and Objectives

Over the next year, we expect to have a new version of the Community Climate System Model, CCSM-2. We expect that it will produce improved simulations of the mean climate and climate variability and have reduced deep-ocean drifts. Once this has been achieved, we will perform an extended, multicentury simulation of the recent past equilibrium climate. The data will be made available to the CCSM community so that they can compare the new model simulation with those of the CSM-1.

It is important that the CCSM-2 continue to be used to study anthropogenic climate change. Accordingly, we expect to perform a new climate of the 20th century experiment and compare the results to those produced by CSM-1. We expect to use the next model to run ensembles of simulations, using scenarios developed by the IPCC and others. We expect that CCSM-2 will contribute to the next National Assessment of Climate, due in or about 2004, and to the next IPCC report, due in 2005.

We also expect that the CCSM-2 will be used for some new types of experiments. The Biogeochemistry Working Group, for example, has begun planning the Flying Leap Experiment. In it fossil fuel carbon emissions will be specified; carbon will be actively advected through the system, dissolved in and released from the ocean, and taken up by the land surface; and atmospheric concentration of carbon will be determined as a residual of these interactive processes. How well the modeled CO_2 concentration in the atmosphere resembles observations will depend on the model components being developed. It is clear that this type of experiment will require a lot of model development and testing. It seems likely that the first experiment will require refinement and further model development and that subsequent experiments will be necessary to answer questions about the carbon budget. This work will likely continue through the entire next five-year period.

We expect that the next five-year period will be characterized by increased model complexity and capability, with the model being used for more experiments that have not yet been attempted. For example, these could include studies of recent climate change due to observed anthropogenic change in land surface properties or climate change and its consequences for ecosystem succession. Exactly which experiments will be performed depends on the rate of model development and validation and the availability of computer time. During this five-year period, the SSC will have to continually evaluate the status of the model and its readiness for possible experiments and set priorities on how to use the computer resources that are available.

B. Model Development and Improvements

1. Atmosphere Model

The CCM3 has produced much better simulations than the earlier CCM versions. However, there are many opportunities to improve specific features in these simulations, some of which will require more sophisticated treatments of physical processes critical to the maintenance of the climate system. Our goal over the next five years will be to obtain more realistic simulations, particularly with respect to the surface energy and momentum budgets and the proper representation of transient phenomena. This includes the realistic simulation of tropical wave activity, including the Madden-Julian Oscillation (MJO) and the Quasi-Biennial Oscillation (QBO).

To facilitate development, a comprehensive diagnostic/evaluation infrastructure is needed. The Atmosphere Model Working Group (AMWG) has proposed adoption of the World Climate Research Programme's (WCRP) Working Group on Numerical Experimentation Standard Diagnostics of Mean Climate as a starting point. The AMWG will attempt to forge stronger links with other working groups to develop the capability to diagnose important modes of variability in the standard diagnostic infrastructure package.

The physical parameterizations to be included in the next atmosphere model are of great importance. Work is under way to better understand the distribution of shortwave energy between the surface and atmosphere. Recent observations suggest that climate models significantly underestimate the amount of atmospheric shortwave absorption. Sensitivity studies will be carried out to study this effect in the atmospheric model. However, the exact solution to this problem must await the identification of the physical mechanism for this absorption.

Work is also under way on moist convection. Many global model simulations suggest that the existing cumulus parameterizations do not reproduce the episodic nature observed in deep convection. Several investigators are exploring physical mechanisms for more realistic triggering of moist convection by generalizing the convective closure and incorporating more realistic cloud models. We expect to continue improving the atmosphere model's physics over the next five years.

Another long-term goal is to improve the physical linkages between the parameterizations for convection, stratiform clouds, radiation, and turbulence. This will require linking cumulus detrainment to stratiform cloud properties, linking predicted paths for liquid and ice water to cloud optical properties, and linking planetary boundary layer (PBL) stratus clouds to the PBL turbulence parameterization.

The coupled model simulations reveal some deficiencies that are related to the use of a spectral code for the atmosphere. A multiyear average of low-level clouds, for example, gives an unrealistic standing wave pattern in cloudiness near the Andes. Studies show that marine stratus formation is very sensitive to the degree of orographic smoothing used. In addition, we expect that the CCSM will be increasingly used for chemistry-climate interactions. It would be more convenient to have a dynamical scheme that was inherently conservative of chemical tracers. We will compare three possible dynamical cores for the next atmosphere model: the present spectral model, a reduced-grid semi-Lagrangian model, and the Lin-Rood model. We hope to decide which model to use within a few months. After that, we will consider how much parallelization to build into the code. Our goal is to be able to run a tropospheric configuration of the atmosphere model with at least 50% higher horizontal resolution (approximately T63-L30) and with a minimum of spurious numerical interactions.

2. Land Processes

Exchanges of energy, water, and momentum between the land surface and atmosphere must be provided to the atmosphere on short time scales (compared to a day) to adequately represent the couplings to boundary-layer processes and moist convection. These fluxes have substantial feedbacks on modeled precipitation, surface temperatures, and other aspects of climate simulations. Inputs from the atmosphere of precipitation and net radiation, as controlled by moist atmospheric processes, are also major determinants of surface climates. Soil and vegetation establish energy balances and temperatures and require geographically detailed data sets to provide their distributions and properties. Also important for fluxes is the loss of water by runoff and its storage in lakes and wetlands. Carbon fluxes to leaves must be calculated to determine water fluxes from leaves. Because of this dependence and a strong dependence of soil biogeochemistry on soil moisture and temperature, the land surface model provides a driver of biogeochemical and ecological processes.

Land models depend on descriptions of seasonally and interannually varying vegetation cover and leaf densities, as well as maps of different types of vegetation according to their architectures, leaf morphologies, and growth rates. These types of vegetation may change over decades or centuries, according to their interactions with the climate system. Past prescriptions have specified the requisite information as simple time invariant or seasonally varying data sets. However, the current scientific questions to be addressed require modelers to specify this information either for individual years or through interactive models of the vegetation dynamics. These two approaches are complementary and should help validate each other.

The land component of a climate system model has three major logical elements that must each be constructed. These are the core single-column model, the externally prescribed spatially distributed data sets needed for its boundary conditions and validation, and the scaling laws that map between its single point fluxes and the spatially averaged values needed by or provided by the atmosphere. Past approaches with simpler models have tended to combine these three constructs, e.g., by assuming an equivalence between point and area-averaged processes or by including scaling algorithms as part of the physical parameterizations of the point model. However, separating the three separate elements should provide a framework that allows greater robustness across platforms, more interchangeability of codes and data between modeling groups, and greater participation by specialists involved with subissues.

The Land Model Working Group has completed a prototype, core single-column land model, designated the Common Land Model (CLM0). We propose that it should replace the current Land Surface Model. Because the algorithms for scaling between land point and grid square are not mature, initial implementations will assume, where needed, a simple equivalence between point and grid square. Some of the most significant subgrid-scale variations that should be addressed for future models are those in precipitation, radiation (because of subgrid cloudiness), topography, water table, vegetation and soil properties, and leaf wetness. We will soon improve the CLM0's point treatment of hydrological runoff and its coupling to biogeochemical processes. In future versions, runoff linked to routing schemes should be able to generate seasonal and interannual variations in wetlands. Biogeochemical schemes for land need to address the distributions not only of carbon, but also of the other commonly limiting nutrients, as provided by nitrogen and phosphate ions. Root distribution and function are major elements in linking soil water to soil biogeochemistry.

As for the scaling element, there is still no generally accepted way to provide global vegetation data to a land model. Past modeling has commonly substituted descriptions of broad ecosystems for data. These descriptions complicate the relationship of modeled vegetation parameters to observational data, which usually refer to individual species. The alternative of individually representing each plant species in the model is impractical. It may be adequate to lump together broad plant functional types, but this approach cannot currently be supported by observational data with any degree of accuracy or possibility of validation. However, satellite data currently are mapped into broad ecosystems, primarily because of the perception that this classification meets the requirements of the climate modeling and ecological communities. The remote sensing community is developing the capability of interpreting individual pixel radiances as fractions of different elements of land cover. Hence, a demonstration that plant functional types are more useful should result in the development of effective new algorithms for satellite data to provide this information. A major objective of our development of the CCSM land modeling framework will be to promote software structures that facilitate the coupling of biogeochemical and ecosystem models to the land model. Making this coupling happen will require collaborations among the relevant communities of experts.

3. Ocean Model

The central problem of modeling the ocean for climate studies is to predict the divergence of the fluxes of properties that are exchanged between the ocean and the other components of the climate system, e.g., heat, fresh water, and dissolved gases. To minimize climate drift, these predictions must be accurate in their time mean. For reliable predictions of the transient behavior of the climate system, they must also be accurate in their temporal variations on time scales of the problem at hand (potentially from diurnal to millennial).

The current generation of ocean models, at resolutions that are practical in coupled climate integrations, can provide good simulations of variations in mass transport on time scales from days to seasons. This success is relatively insensitive to details of the model formulation, e.g., vertical coordinate, parameterizations of dissipation, etc. However, at interannual-to-millennial time scales and for the equilibrium state of the ocean, current models show tremendous sensitivity to details of the representation of processes, such as deep convection, boundary-layer dynamics (lateral, surface, and bottom), interior redistribution of properties by mesoscale eddies, and diapycnal mixing. These processes can be identified with the branches of the global thermohaline circulation, such as sinking at high latitudes (often within semi-enclosed seas), flow through narrow straits and over sills, rapid transport through deep and surface western boundary currents, weak and nearly adiabatic flow through the interior of ocean basins, and the return of deep water to the surface through spatially inhomogeneous mixing processes. Progress in ocean modeling for climate studies must address these sensitivities. Models certainly must be able to provide quantitative predictions of the ocean's response to changes in surface buoyancy fluxes, and hence of the role of the ocean in global climate change.

The next generation ocean model used in the CCSM will need the best physical parameterizations available to be able to address the issues developed above, and it must be able to run on the computers available in the NCAR Climate Simulation Laboratory or at other facilities where the CCSM may be run. Accordingly, the Parallel Ocean Program (POP), originally developed at Los Alamos National Laboratory, has been chosen as the base code for the next version of the CCSM. The model was specifically designed for parallel supercomputing, and it runs on a variety of platforms. We have implemented the physics used in the current code—the K Profile Parameterization (KPP) of vertical mixing and the Gent-McWilliams (G-M) parameterizations of mesoscale eddies—in POP and have extensively evaluated the results over the past year. In addition, we have included increased resolution in the tropics and a new anisotropic viscosity scheme, which together have the beneficial impact of improving the equatorial current structure (i.e., much more realistic current speeds) and increasing the variability in the tropics.

Experiments have also been conducted that include land runoff forcing of the ocean model, which should lead to improvements in surface salinity patterns. This model has been judged to be a suitable replacement for the previous ocean model. New equilibrium ocean-alone solutions are expected for 3-degree and 2-degree resolutions. As model development at higher resolutions continues, equilibrium solutions are also expected for 1-degree and possibly 1/2-degree resolutions, depending on the availability of computer time and the progress in model development.

Progress in the numerical representation of the ocean physics in the CCSM will require work in four categories: ongoing development and testing of model physics parameterizations; improvements in model numerical algorithms and code framework; exploration of resolution dependence; and evaluation of the mean state and temporal variability of the ocean solutions against observations. Topics to be addressed include:

a. <u>Interior Diapycnal Mixing Processes</u>. The parameterization of interior diapycnal mixing processes, i.e., those occurring outside the surface and bottom boundary layers, is still quite crude in the CCSM ocean component. More physically based schemes need to be developed, implemented, and tested in the CCSM to improve the representation of both the mean ocean state and its variability. A leading candidate for the energy source for interior mixing is the breaking of internal waves generated through the interaction of tidally generated currents with topography. Another mechanism known to be responsible for interior mixing is double diffusion.

b. Eddy Lateral Mixing of Tracers. Testing will soon begin on the Visbeck modification of the G-M parameterization, thus allowing for local adjustment of the isopycnal mixing terms as a function of baroclinic structure. The possibility of more refined mesoscale eddy parameterizations for higher resolutions also needs to be explored.

c. Eddy Lateral Mixing of Momentum. Refinements to the anisotropic momentum mixing scheme developed in the NCOM framework have been incorporated into POP, but testing is still incomplete. In addition, other schemes based on nonlinear viscosity formulations (e.g., flow dependence) need to be tested at the resolutions relevant to CCSM applications.

d. Natural Surface Boundary Conditions on Water. Although POP is a free surface code, it does not yet permit the exchange of mass, i.e., freshwater fluxes through the sea surface. At present, freshwater fluxes must be re-interpreted as a fictitious and unphysical salinity flux before being applied to the ocean model. Moving to a more physically based specification of material fluxes of mass needs to be explored.

e. Bottom Boundary Layer. The simple bottom boundary layer scheme developed in the NCOM model needs to be ported to the POP model framework, with additional development including more sophisticated detrainment algorithms and adaptation to the partial cell bottom topography. The problem of simulating the overflows of the northern North Atlantic Ocean provides an important test of the bottom boundary layer for which relatively good observations and process models exist.

f. Representation of Topography. Partial bottom cells are a promising method to improve the representation of topography in a z-coordinate model framework. Work is under way to incorporate this methodology in the POP code.

g. Numerical Advection Algorithms. As resolution and material complexity (e.g., addition of biogeochemically active tracers) of the ocean simulation's increase, the need for better advection algorithms becomes more pressing. The desirable properties of monotonicity, low dissipation, computational stability, and efficiency on clustered shared-memory-parallel architecture must be evaluated.

h. Horizontal Resolution. Better understanding of the resolution dependence of the ocean model solutions is required. There are issues, for example topographic representation, that are guaranteed to improve with increased resolution. It is notable, however, that increasing spatial resolution alone is not generally considered the most promising route to improved ocean simulations in coupled climate models in the near to medium term, as most of these critical processes occur at scales that will remain unresolved for several more generations of high performance computers. The use of eddy-permitting models in climate simulations needs to be further explored, evaluating their benefits and the changes in subgrid-scale parameterizations that may be required.

i. Grid Design. The generalized coordinate formulation of the POP code opens up the possibility of designing grids that optimize the distribution of grid points around the global ocean. Initial, very rudimentary experiments along these lines are under way, but many possibilities remain to be explored.

j. Code Design and Performance. As the CCSM effort as a whole moves towards more integrated design and development practices, the ocean model component must track them to leverage manpower, improve system reliability and maintainability, and to assure performance portability of the system across the range of available architectures. Ongoing efforts to implement common code frameworks, model output standards, and analysis tools will also be continued.

k. Upper-Ocean Model. An upper-ocean model (UOM) has been designed and implemented in NCOM. Its essential simplification compared to a conventional full-depth model (FDM) is the specification of an abyssal climatology for material properties. The UOM and FDM solutions agree well in both the mean state and short-term climate fluctuations, and even for cases where the model parameters and forcing are modestly inconsistent with the UOM's abyssal climatology. The primary advantage of the UOM is its reduced spin-up time, requiring a period of about 30 years to reach an equilibrium state. An upper-ocean model can be a useful, efficient tool for studies of coupled climate dynamics and sensitivity to forcing fields and model parameters and for hypothesis testing about the roles of the abyssal ocean. This UOM will be implemented into POP when it reaches a more mature state.

l. Coupled Ocean, Sea-Ice Simulations. The deep-water formation rates and equilibrium water mass properties are sensitive to the under-ice heat and freshwater fluxes in relatively small, localized regions. The current ocean-alone equilibrium experiments use strong restoring to observed temperature and salinity distributions in ice covered regions. Improvements, particularly in the Southern Ocean, have been found in some coupled ocean-ice spin-up experiments, and the future direction will tend towards coupled rather than stand-alone simulations. This will also require exploration of issues, such as the interaction of the KPP surface boundary layer scheme with a heterogeneous upper boundary consisting of open water, leads, and multi-thickness sea-ice distributions.

4. Sea-Ice Model

In virtually every scenario of warming due to greenhouse gases run in climate models, the largest increases in temperature occur in the high latitudes, especially near the edge of the sea ice. Meanwhile, observations show changes in the water mass structure of the Arctic Ocean, thinning of Arctic sea ice, and major icebergs breaking off the Antarctic ice shelves. Changes in the polar climate are becoming apparent, and understanding these changes is of great importance. The CCSM needs an improved sea-ice model that reliably simulates the sea-ice processes that are important for climate and the ways these may change in the future.

In CSM-1 the state of the sea ice in each grid cell is represented by the following dependent variables: ice concentration, ice thickness, snow depth, surface temperature, ice temperature, and ice velocity. The evolution of the ice velocity field is simulated using a two-dimensional momentum equation, which balances the air stress, water stress, divergence of internal ice stress, ocean surface tilt, and Coriolis acceleration. The internal ice stress is calculated from the strength, which depends on ice thickness and ice concentration, and the strain rate, which derives from the ice velocity field. The momentum equation is solved using an iterative procedure that treats the ice as a cavitating fluid; that is, the yield curve is a straight line in the plane of principal stresses.

Ice thickness and ice concentration evolve according to continuity equations that represent the combined effects of thermodynamic ice growth (and melt), advection, and redistribution due to convergence and divergence in the velocity field. Thermodynamic growth includes contributions at the top and bottom surfaces of the ice fraction, as well as lateral growth and melt due to interactions between the ice fraction and the open water fraction in the grid cell. Growth and melt at the top and bottom depend on the heat balances at these surfaces, including the vertical conductive heat flux through the ice. In this way the ice temperature is coupled to the ice mass balance. Ice can also form in the upper layer of the ocean due to heat loss from leads.

Additional quantities needed to integrate the CSM-1 sea-ice model are prescribed as constants or formulated in terms of the dependent variables. For example, the aerodynamic roughness and specific heat of sea ice are prescribed constants, and spectral surface albedoes are formulated as functions of snow depth and surface temperature.

Results from the CSM-1 sea-ice model are reported by Weatherly and others. A number of features in the temporal and spatial variability of the simulated sea ice match qualitatively with the present observed climate, especially in the Southern Hemisphere. In addition, long-term drifts of sea-ice parameters appear to be acceptably small in the 300-year integration. On the other hand, the simulated sea-ice extent in both hemispheres is significantly larger than observed, especially in the Northern Hemisphere winter. The spatial distribution of ice thickness in the Arctic Ocean is biased with thickest ice in the Chukchi Sea north and west of the Bering Strait instead of as observed north of Ellesmere Island and Greenland, and equatorward ice transports were oversimulated all around Antarctica. Diagnostic analyses and sensitivity studies performed by Weatherly and others indicated that the method of solving the cavitating fluid rheology on the CSM-1 ocean grid (spherical polar) produced spurious ice convergence. In addition, the prescribed aerodynamic roughness of sea ice was too high, leading to an oversimulation of air stress in the momentum equation. The discrepancies in simulated sea-ice thickness, extent, and velocity affect the simulated ocean surface buoyancy flux associated with the transport of relatively low salinity sea ice from growth regions to melting regions. This buoyancy flux controls ocean convection in high latitudes with major impacts on the thermohaline circulation.

Over the past 2 to 3 years, the CCSM Polar Climate Working Group (PCWG) has organized and promoted activities to improve the CSM sea-ice model. Specific objectives for the CCSM-2 release are as follows:

- Implement and test a plastic ice rheology with an elliptical yield curve that represents shear stresses as well as normal (compressive) stresses;
- Implement and test a multiple category sea-ice thickness distribution and investigate the sensitivity of the results to the number of categories;
- Implement and test enhanced sea-ice thermodynamics: resolve vertical temperature profiles in all ice thickness categories; apply energy conserving boundary conditions at the top and bottom surfaces of the sea ice; investigate explicit modeling of melt ponds with an associated albedo parameterization;
- Eliminate the spurious ice convergence encountered in CSM-1 near the North Pole, where the model grid points are closely spaced;
- Program the sea-ice model to run on the same grid as the ocean model to reduce the amount of interpolation;
- Program the model to run efficiently on the distributed-shared-memory computers that are being installed and brought online at NCAR;
- Prescribe more realistic constant parameters, such as the aerodynamic roughness length over sea ice; and
- Test the performance of new versions of the CCSM sea-ice model using a stand-alone ice modeling framework and comparing results to observations. This includes testing overall performance in simulating observed climatology and testing parameterizations against more detailed observations.

Significant progress has been made as follows:

- A sea-ice model called "CICE" has been developed at Los Alamos National Laboratory, with an elastic-plastic ice rheology (elliptical yield curve), algorithms suitable for distributed-shared-memory computing, and using the POP model grid. The POP model has been selected for use as the ocean component of CCSM-2, so this addresses the grid compatibility objective. The pole of the POP coordinate grid is over land, and numerical problems associated with closely spaced grid points have been reduced to an acceptable level for resolutions of 2 degrees and coarser. The CICE model is serving as a development framework for the CCSM-2 sea-ice model and has been implemented at NCAR;

- A multiple category sea-ice thickness distribution with enhanced thermodynamics (but no explicit melt ponds) has been developed at the University of Washington and implemented at NCAR with the CICE model;

- The aerodynamic roughness of the model sea ice is now prescribed at a more realistic value, and other parameters are being checked by comparison with observations;

- A viscous-plastic sea-ice model with elliptical yield curve was developed at the University of Washington and implemented at NCAR, running on a north polar grid. This model was used in a short-term (40-year) integration of the fully coupled CSM, and it did not exhibit the spurious ice convergence near the North Pole. This model has been programmed for general orthogonal coordinates (e.g., the POP grid), but this program has not been tested; and

- An ice-only modeling framework has been established at NCAR and initial integrations of the new model elements have been performed, forced by both CCM output and NCEP analyses. Preliminary analysis indicates the new framework is running OK. Further analysis and additional integrations are needed to determine how the changes affect the overall sea-ice simulations and climate model sensitivity.

Continued progress in CCSM sea-ice modeling will be sought by comparison of simulation results with observations of present climate and climate variability from a variety of sources, including satellite remote sensing of ice extent, ice area, and ice motion, submarine sonar measurements of ice thickness, and drifting buoy measurements of ice velocity. In addition to testing model results against climatology, it is important to evaluate parameterizations that affect the sensitivity of the CCSM ice model (and hence CCSM) to perturbations. Here the approach is to compare the behavior of the parameterizations to detailed observations such as the results from process studies (e.g., the ongoing Surface Heat Budget of the Arctic Ocean (SHEBA) project). Of particular interest in this regard are simultaneous observations of surface albedo and surface state (melt ponds, snow cover, ice thickness distribution, ice concentration, etc.). Members of the PCWG are working actively in these areas, including assembling data sets especially suited for model evaluation. The PCWG will consult with the investigators of the WCRP's Arctic Climate System Study (ACSYS) Sea Ice Model Intercomparison Project about their results as part of the evaluation of the CCSM-2 sea-ice model development.

The CCSM sea-ice model is important, but it remains only one aspect of high latitude climate dynamics. The PCWG is also active in model development and analysis involving the atmospheric and ocean components of CCSM. In particular, the PCWG places a high priority on improving the simulation of the mean annual cycle of sea level pressure and surface winds over the polar regions. Even when forced by realistic SSTs, the CCM atmosphere does not simulate the mean summertime low pressure cell over the

Arctic Ocean, and it does displace the mean wintertime high pressure cell significantly poleward of its observed location. These discrepancies force unrealistic ice motions and contribute significantly to the errors in simulated ice thickness, extent, and transport. The PCWG is investigating how CCM horizontal resolution, orography, and surface heating affect the simulated sea level pressure fields over the polar regions. In addition, the PCWG has noted significant differences between CCM simulated and observed clouds and radiation in the high latitudes. PCWG model development activities in this area are being coordinated with the SHEBA and the First ISCCP (International Satellite Cloud Climatology Program) Regional Experiment-Arctic Cloud Experiment (FIRE-ACE) projects, which specifically address the radiative interactions of clouds and the surface over sea ice.

Simplifications made in the initial NCOM ocean component of CSM essentially precluded realistic comparisons with the observed Arctic Ocean circulation because the Bering Strait and the Canadian Archipelago were closed in CSM-1 and the river runoff, which is so important to the stratification of the Arctic Ocean and the high North Atlantic, was distributed in a highly simplified, ad-hoc manner. The plan for the CCSM-2 ocean component includes opening the Bering Strait and a channel through the Canadian Archipelago, as well as implementing a more realistic continental runoff model as part of the Land Surface Model. These improvements augur well for the future applicability of the CCSM to problems of polar climate and arctic system science.

The PCWG also intends to:

- Simulate and diagnose polar climate variability on interannual-to-interdecadal scales, e.g., the Arctic Oscillation and other modes of variability involving the polar atmosphere;

- Diagnose the simulated polar climate in the CCSM Climate of the 21st Century integrations; and

- Use CCSM-2 to diagnose the hydrologic and freshwater budgets of the Arctic and their influence on the thermohaline circulation of the Atlantic and the world ocean.

C. Scientific Challenges

1. Chemistry and Climate Change

Changes in the chemical composition of the atmosphere are the fundamental driver of anthropogenic climate change. Observational records of the chemical composition of the atmosphere indicate dramatic changes in concentrations of trace gases, such as carbon dioxide, ozone, methane, nitrous oxide, and the CFCs. These changes are directly related to industrial and agricultural activity in the 20th century.

For the past three years, the major activity of the Chemistry and Climate Change Working Group (CCCWG) has been to define forcing factors for the 20th and 21st centuries and to carry out simulations of these time periods. The CCCWG has been folded into the Biogeochemistry Working Group (BGCWG) and the Climate Change and Assessment Working Group (CCAWG). Future simulations of the 20th century will consider natural forcing by variations in solar luminosity and volcanic dust.

Currently, most climate change studies prescribe chemical changes in climate system models and do not allow interactions between the climate and chemical systems. However, we know that the coupling of these systems produces important effects in many cases. For example, chemical tracers are affected by convective-scale transport. Cloud property changes affect aqueous-phase production rates. Our goal for the next five years is to work toward a fully coupled chemistry model within the CCSM.

Aerosols affect the climate system in a number of ways. Aerosols reflect and absorb radiation. They also modify cloud properties and affect the amount of radiation scattered—the "indirect effect." Aerosols interact with chemical processes as sites for heterogeneous reactions and by altering the actinic flux for photolysis. Improved simulation of aerosol effects in the CCSM is a major goal.

Current CCSM simulations rely on prescribed or highly constrained distributions of chemical species. An integrated chemical model is required to simulate important interactions between chemical species and the climate system. In the troposphere, ozone will be the first species to be considered, along with the related cycles that affect the production and destruction of ozone. In the stratosphere, it is also important to consider the interaction of ozone and climate change. A stratospheric chemistry model will be integrated into a middle atmosphere model, which is under development.

The development of chemistry models will require the BGCWG and the CCAWG to collaborate closely with other working groups. Clouds play an important role in chemical processes by acting as sites for aqueous-phase reactions. Changes in the amount of clouds, the amount of liquid water in clouds, and their lifetime will result in changes in chemical production and removal of species through wet deposition. This will require simultaneous development by the AMWG and the BGCWG and CCAWG.

In addition, natural sources of species can be related to specific vegetation types. Destruction of forests through burning also affects tropospheric chemistry. Consideration of these and other processes will require close collaboration between the Land Model Working Group and the CCCWG.

2. Middle Atmosphere Model

The middle atmosphere is an important component of climate system modeling because it plays an important role in climate variability and climate change. Even the upper atmosphere (above ~80 km) may play a significant role in climate variability, since most of the observed variability in the solar output occurs at wavelengths too short to penetrate even to the stratosphere. Certainly, the largest and most unambiguous climate changes due to increasing atmospheric CO_2 will occur in the thermosphere.

The impact of stratospheric variability on climate and the role of the stratosphere in climate change are currently open questions. Several studies suggest that changes in the stratospheric circulation have a significant impact on the troposphere, altering planetary wave structures and storm track positions. The dynamics of the stratosphere is dominated by the interaction of dynamical forcing by waves propagating upward from the troposphere and radiative forcing by solar heating due to ozone. The planetary-scale waves propagating upward from the troposphere affect the stratosphere directly. However, smaller-scale gravity waves propagate through the stratosphere into the mesosphere and lower thermosphere, where they deposit momentum and affect the stratosphere through "downward control." To understand the role of the stratosphere in climate variability, the coupled variability of dynamics and ozone in the stratosphere must be modeled and understood.

The expected cooling in the stratosphere, due to increasing CO_2 concentrations in the atmosphere, is much larger than the expected increases in surface and tropospheric temperatures. This result is expected from the fundamental physics of radiative transfer and is independent of the model used and of the magnitude of the water vapor feedbox in the climate system. Because ozone chemistry is temperature dependent, changes in stratospheric temperature will produce changes in stratospheric ozone, independent of any changes in circulation or sources of other chemical compounds. Current climate models do not adequately represent the stratosphere and do not include feedbox between ozone and dynamics. However, preliminary studies with simplified models suggest that climate sensitivity may be different when the stratosphere, including ozone chemistry, is better represented. Research on the climate effects of the stratosphere requires a model that extends from the surface through the mesosphere and includes interactive ozone chemistry.

Several studies have suggested that much of the climate variability observed over the last several centuries can be explained by variations in solar irradiant. There has also been considerable discussion of the observed correlation between the 11-year solar cycle and tropospheric temperature and geopotential patterns. Satellite observations of solar irradiance over the last 20 years show that most of its variation occurs in the extreme ultraviolet (wavelengths shorter than 200 nm). Radiation at these wavelengths is almost entirely absorbed in the mesosphere and thermosphere. In fact, the radiative transfer codes in current climate models generally do not include wavelengths shorter than 250 nm because they do not penetrate into the vertical domain resolved by these models.

Any effects of solar irradiance variations on the troposphere and surface climate must come indirectly, through changes in the stratospheric ozone distribution and circulation. To understand the natural variability of the climate system, it is important to determine whether variations in solar irradiance can play a significant role. Addressing this question will require models that extend vertically through the mesosphere and include interactions between ultraviolet radiation, ozone chemistry, and dynamics.

Variations in thermospheric properties are partly driven by solar variations and partly by forcing from the lower atmosphere. Understanding these effects requires a model that extends upward from the surface with realistic variability.

At least two satellite projects—the high-resolution dynamics limb sounder (HIRDLS) and the thermosphere-ionosphere-mesosphere-energetics-dynamics (TIMED)—will be taking observations of the middle atmosphere in the next few years. Interpreting HIRDLS and TIMED observations will require coupled dynamical and chemical modeling of the middle and upper atmosphere. TIMED soundings will also be significantly affected by thermospheric variations, and we should make use of modeling studies to understand these effects.

There is currently a middle atmosphere version of CCM3 (MACCM3) that extends from the ground to 84 km, which is used to investigate the dynamics of the stratosphere and lower mesosphere. The radiation parameterizations currently employed are only valid to ~65 km, largely due to the breakdown of the local thermodynamic equilibrium (LTE) assumption. However, the dynamics of the upper stratosphere and lower mesosphere are strongly influenced by gravity waves that propagate up from the troposphere and break between 65 and 100 km, depositing energy and momentum. We chose the current upper boundary of MACCM3 to resolve at least part of the gravity-wave-breaking region in all seasons but not extend too far into the non-LTE region.

In response to the scientific problems requiring an atmospheric general circulation model (GCM) with a vertical domain from the surface into the thermosphere, MACCM3 is now being extended upward to the turbopause (~120 km). The extension of the MACCM3 will require incorporating new physics and chemistry for investigation of processes operating in the upper mesosphere and lower thermosphere and couplings between atmospheric regions. The resulting model will form the basis for adding further thermospheric physics and chemistry, much of which is currently operating in the thermosphere-ionosphere-mesosphere-electrodynamics (TIME) GCM, to allow the model to be extended upward for several hundred kilometers, replacing the TIME GCM as a community model for upper atmosphere research. The CCM is the atmospheric component of the CCSM, and its upward extension will still be capable of operating with coupled ocean and sea-ice models. A major application of the model will be to investigate the effects of solar variability on the atmosphere and climate system.

The extension of MACCM3 to 120 km will allow the investigation of dynamics, chemistry, and solar-terrestrial couplings in the upper middle atmosphere. New data from the NASA Upper Atmosphere Research Satellite (UARS) and NSF Coupling, Energetics, and Dynamics of Atmospheric Regions (CEDAR) programs indicate important interactions between dynamics, chemistry, radiation, airflow, and electrodynamics that need to be investigated using a comprehensive model of the atmosphere. New satellite data for this region will become available over the next few years, especially from TIMED and HIRDLS.

At present, NCAR has two separate GCMs for the lower and middle atmosphere (the CCM and the Model of Ozone and Related Trace Species or MOZART) and a third for the middle and upper atmosphere and ionosphere (TIME). The TIME GCM includes chemistry, but the CCM does not, and it is not coupled to MOZART, which is a chemistry model. All three models have progressed greatly over the years, and they have improved our overall understanding of the physical and chemical processes operating in their respective regions of investigation. Yet each model is limited by its need to specify boundary conditions to represent couplings between atmospheric regions. We are proposing to combine our expertise of each atmospheric region into a single model of the entire atmosphere to avoid the imposed boundary conditions and to be able to address a wide range of new problems dealing with couplings between atmospheric regions. An additional benefit would be the adoption of a common numerical framework that will reduce the resources required for code development and maintenance.

First-year activities:

- extend the MACCM vertical grid upward from 84 km to 120 km;
- include the non-LTE infrared radiation code in the MACCM;
- include, as appropriate, changes to the rates of solar radiative heating and dissociation for the upper mesosphere and lower thermosphere;
- incorporate molecular diffusion effects on composition, temperature, and dynamics due to the large mean free path in the upper mesosphere and thermosphere;
- extend the gravity-wave parameterization to account for the transition from wave breaking to dissipation through molecular diffusion above the turbopause;
- incorporate the appropriate chemical cycles into a coupled model (the current version of the middle atmosphere chemical model is not interactive with dynamics); and
- perform numerical experiments as necessary to test and validate physical and chemical processes.

Following-year activities:

- use the extended MACCM for the scientific studies discussed above, including climate variability and climate change;
- add additional thermospheric physics and chemistry, including ion drag, to allow the extension of the model to 500 km, replacing the current TIME GCM; and

- explore the impact and feasibility of using the MACCM as the standard atmospheric component in coupled CCSM simulations.

3. Biogeochemistry

The overall goal of the Biogeochemistry Working Group (BGCWG) is to improve our understanding of the interactions and feedbacks between the physical and biogeochemical climate systems under past, present, and future climates. Key short-range scientific objectives are to study the carbon cycle's natural interannual variability and forced decadal-to-centennial response to perturbations (e.g., climate warming, land-use change). This will require development, evaluation, and coupling for a suite of global, prognostic biogeochemical component models (land, ocean, and atmosphere) within the CCSM. Extensive data analysis and diagnostic modeling studies for the period of the last two decades, when good data on atmospheric composition and from satellite remote sensing exist, will also be used to evaluate model skill and determine underlying processes.

Our focus on a set of carbon cycle simulations, ranging from partially to fully coupled, is based on the primary role of anthropogenic CO_2 emissions in potential climate change, the availability of a global network for atmospheric CO_2 and related compounds, and the readiness of the various component models for the ocean, atmosphere, and land. The BGCWG intends to expand into other radiatively and chemically important species such as CH_4, O_3, organic halides, and sulfur species as improved models and resources become available.

Growing concern over the issue of climate change has focused efforts on understanding the temporal evolution, climate impact, and potential feedbacks of biogeochemical forcing factors, such as radiatively active trace gas species, natural and anthropogenic aerosols, and land-use change. The future levels of atmospheric greenhouse species, such as CO_2, have become one of the major uncertainties associated with climate predictions through the next few centuries. Fossil fuel emissions and anthropogenic land-use changes have resulted in an increase in atmospheric CO_2 concentrations over the last 150 years from a pre-industrial level of about 280 parts per million (ppm) to 365 ppm at present, and "business as usual" scenarios project values as high as 700 to 800 ppm by the end of the 21st century.

For the recent decade of the 1980s, fossil fuel emissions and tropical deforestation released roughly 5.5 gigatons of carbon per year (GtC/year) and 1.5 GtC/year, respectively. About 40% of this, or 3 GtC/year, remained in the atmosphere. The rest must be removed by oceanic and terrestrial sinks, each estimated to contribute about –2 GtC/year over this period. The physical mechanism for the dissolution of excess CO_2 into the ocean is reasonably well understood if not fully quantified, and the terrestrial sink is thought to result from a poorly determined mix of forest regrowth, CO_2 and nitrogen (N) fertilization, and climate effects.

Future projections of atmospheric CO_2 levels are relatively sensitive to assumptions about the behavior of the land and ocean carbon sinks, which are expected to change due to saturation effects and responses to the modified physical climate. On interannual time scales, the absolute magnitude of the CO_2 sinks and their partitioning between land and ocean vary considerably, as demonstrated by the atmospheric CO_2 growth rate, the isotopic composition of atmospheric CO_2 or O_2, and other measures. Paleoclimate records of atmospheric CO_2 also suggest that the global carbon cycle has not remained static, nor is it likely to.

Until recently, research in climate sensitivity and climate change revolved around the response of the physical climate system to specified increases in atmospheric CO_2. Climate model experiments investigated the equilibrium and transient responses to prescribed changes in atmospheric CO_2 concentration and did not take into account the effects of the terrestrial and oceanic systems on the CO_2 growth rate. The interactions of the atmospheric carbon system with the terrestrial and oceanic systems may accelerate or decelerate the atmospheric CO_2 growth rate and hence the rate of climate change. In turn, climate change has serious implications for the carbon dynamics of the terrestrial and oceanic systems and may alter the carbon sequestration potential of these systems.

The BGCWG's scientific effort over the next five years will attack several scientific questions that involve national needs and that may provide the scientific basis for international agreements. The foremost issues are: What are the controls on the interannual variability of land and ocean CO_2 sinks that have been observed over the last few decades? How does interaction with biogeochemical cycles of other elements (N, S, P, Fe) affect the behavior of the carbon cycle? How will the terrestrial and oceanic carbon cycles change with the changing climate? How will these feedbacks alter the growth rate of atmospheric CO_2 and the rate of climate evolution? How will the changes in the climate (and in climate extremes) and in the biosphere influence human welfare? Can and should humans manage the terrestrial and oceanic carbon cycles to obtain the optimal economic, social, and climatic future?

The BGCWG's research activities can be split roughly into four areas: (a) completing the initial component models of the carbon cycles of land, ocean, and atmosphere; (b) using prognostic and diagnostic models for evaluation and process studies; (c) continuing to develop the component models; and (d) exploring the carbon-climate interaction using uncoupled and fully coupled carbon system experiments leading up to and including the so-called Flying Leap carbon experiment.

The main elements controlling the evolution of the atmospheric CO_2 distribution are CO_2 transport and surfaces fluxes coming from the land and ocean: fossil fuel burning, deforestation, photosynthesis and respiration, and the air-sea flux. The current status of each of these with respect to a prognostic model capability is as follows. The atmospheric CO_2 transport comes directly from the CCM3. Existing CO_2 transport calculations from the CCM2 and CCM3, given prescribed surface CO_2 flux forcing, replicate the main features of the observed seasonal CO_2 cycles and meridional gradients at representative stations in NOAA's Climate Monitoring and Diagnostics Laboratory network. The time-space distributions of fossil fuel emissions are reasonably well constrained from historical reconstructions; the same is true for deforestation, but with significantly larger uncertainties. A number of models are available within the CCSM framework to predict terrestrial photosynthesis (LSM, SiB, Biosphere-Atmosphere Transfer Scheme, IBIS) and respiration (Century, CASA, IBIS) fluxes. We plan to use initially a new land biogeochemical model, which is currently under development. The new model combines elements of LSM (photosynthesis, biophysics, leaf area index), Century (soil microbial respiration and nitrogen dynamics), and a new plant model (growth, plant respiration, allocation, nitrogen limitation). On the ocean side, a simple, full-depth carbon biogeochemical model with diagnostic surface production has been created and implemented in NCOM. A fully prognostic version is also under development.

Starting with these existing carbon cycle models, the BGCWG proposes a focused study of carbon-climate interactions and their effect on future aspects of global change. The group will carry out a series of global three-dimensional numerical experiments on carbon-climate interactions. We note at the outset that we do not view the model experiments as simulations. The goal of the experiments is to articulate what we actually know and do not know and to formulate and prioritize the agenda for future research. The strategy is to build our understanding of carbon-climate interactions systematically, progressing from experiments and hypotheses that can be evaluated by ancillary information to experiments that project the interactions of carbon and climate in the future, which are likely to be different from anything experienced in the past 400,000 years. The sensitivity experiments that capture our uncertainties in the processes will be critical to the analysis. We envision three experimental themes:

a. Interannual Experiments. These will investigate the causes of the atmospheric CO_2 variations since the 1980s. Terrestrial carbon models will be forced by the observed climate statistics of the period, while oceanic carbon modules will respond to the changes in circulation forced by the variations in surface exchanges of momentum, energy, and freshwater.

b. Permissible Emissions Experiment. An atmospheric CO_2 concentration (e.g., 1% growth per year) will be specified, and the terrestrial and oceanic carbon modules will be separately forced to estimate the uptake. Two sets of climates will be used, the current climate (from the control run of the CCSM) and an evolving climate with a fixed 1%/year CO_2 growth rate. The residual between the specified growth rate and the calculated terrestrial and oceanic sinks is the anthropogenic emissions that would maintain the specified growth rate. This experiment will also provide a first estimate of the effect of changing climate on the uptake.

c. Flying Leap Experiment. A fossil fuel emission scenario is prescribed and the atmospheric radiation will be forced by the residual of the fossil fuel CO_2 after terrestrial and oceanic uptake has been accounted for. The terrestrial and oceanic carbon uptake will be calculated using prognostic carbon modules that are responsive to changes in climate and circulation.

The research area of carbon-climate interaction is new. The proposed work is only now being initiated by other major modeling groups around the world. The Flying Leap

Experiment above was approved in early 1999 as a joint project between the WCRP and the International Geosphere-Biosphere Programme (IGBP). It will define the scientific framework for understanding how the terrestrial and oceanic biospheres may be affected by, and in turn may alter, the course of atmospheric and oceanic circulation and climate change.

The BGCWG is also developing a complementary research path in diagnostic or inverse modeling. The magnitude, spatial patterns, and underlying mechanisms for the land and ocean CO_2 sinks are not well understood. However, given an atmospheric transport field and some observational constraints, a relatively well developed set of numerical techniques can be applied to solve or invert for the unknown surface fluxes. Sufficient atmospheric data exist to study the mean surface fluxes and interannual variability over the last two decades, determine the relationship of the CO_2 sinks with climate parameters and indices (e.g., temperature, precipitation, Southern Oscillation Index), and evaluate the performance and response of the forward, prognostic models to variability.

Ongoing research for the ocean, atmosphere, and land biogeochemical component models is also required for model evaluation, process and sensitivity studies, and model development. We have identified several cross-domain issues for near-term effort. The incorporation of carbon isotopes (^{13}C and ^{14}C) and atmospheric O_2 and N_2 is crucial for partitioning between ocean and land carbon sinks and for tracking the anthropogenic carbon signal. (Fossil fuel carbon is isotopically light in ^{13}C and has effectively no ^{14}C.) The terrestrial production, atmospheric transport, and subsequent oceanic deposition of dust that contains iron have been identified as important in modulating marine productivity and carbon storage. The ^{18}O isotopic composition of atmospheric water provides a direct coupling of the hydrological and biogeochemical cycles and is a good measure of model behavior because the global distribution of ^{18}O in precipitation is well known. Finally, the atmospheric distributions of the radiatively important species CH_4 and O_3 are a complex balance of surface biogeochemical fluxes, atmospheric transport, and chemical dynamics.

Specific research tasks are also outlined for the individual domain component models. For the ocean, the treatment of ecological processes (upper-ocean production and export and subsurface remineralization) clearly needs to be more sophisticated than that in the current NCOM biogeochemical model. A subgroup plans to develop and evaluate a core marine ecosystem model linked with full-depth biogeochemistry, with multiple phytoplankton and zooplankton sizes, multiple nutrient limitations (N, P, Si, Fe), and dissolved organic matter. Both the NCOM biogeochemical model and core ecosystem model will be migrated to the new POP ocean model. A series of comparisons between modeled and observed ocean tracers (CFCs, tritium, ^{3}He, ^{14}C, abiotic and biotic carbon, anthropogenic carbon) is under way within NCOM as part of the IGBP's Global Analysis, Interpretation and Modeling (GAIM) Ocean Carbon Model Intercomparison Project. These simulations will help us evaluate the circulation of the ocean model and will be used in an ongoing fashion as benchmarks for the evolving physical model framework. Although the present CCSM ocean model does not adequately resolve the role of mesoscale eddies or the coastal oceans from a biogeochemical perspective, preliminary process studies in higher-resolution basin-scale models are in progress. These results will feed into parameterizations for the full global model.

The current emphasis within the atmospheric biogeochemical component is on model evaluation and application rather than development. A main objective is to complete a suite of exercises validating tracer transport as part of the IGBP/GAIM TransCom activity (an atmospheric transport intercomparison project). The TransCom 1 model intercomparison, which included the CCM3, clearly demonstrated that GCMs with a PBL scheme for the so-called rectified tracers, such as vegetative CO_2, provide solutions that are qualitatively different from those of models without such schemes, because the surface fluxes of these tracers are strongly correlated with boundary mixing on diurnal and seasonal time scales. The second phase of TransCom deals with the transport of a passive, anthropogenic tracer species, $SF_{6.}$ The third TransCom effort focuses on simulating the atmospheric CO_2 distributions from a large set of surface flux basis functions. Inversions based on observed atmospheric CO_2 will then be completed for each model to determine the spatial patterns and magnitudes of the implied ocean and land CO_2 sinks. The BGCWG is actively working to ensure that TransCom3 is completed with the CCM3.

On the terrestrial side, the BGCWG has identified a number of needs with respect to model development. One is to incorporate a mechanistic phenology into the LSM or the CLM, which is a prognostic rather than specified annual cycle of vegetative leaf area index. The inclusion of a prognostic vegetation scheme similar to that in the IBIS model would also be desirable as it would allow for variations in land cover and plant type in response to climate forcing. Finally, the active transport of biogeochemical species by rivers would allow the group to study a number of issues, ranging from the recent hypothesis regarding carbon sequestration in reservoirs to anthropogenic eutrophication of the coastal oceans to riverine iron input.

The success of the BGCWG depends on maintaining strong links with other CCSM working groups. The biogeochemical models are by necessity set in the physical climate system as it is represented by the work of the land, ocean, and atmosphere working groups. In particular, good communication among the working groups is required to ensure that the appropriate hooks for the biogeochemical modules are retained (particularly in the development of the new CLM) and that physical and biogeochemical model development progress in tandem in a number of key areas (e.g., mechanistic terrestrial phenology, river routing, the atmospheric boundary layer, the coastal ocean).

4. Paleoclimate

For the past three years, the major activity of the Paleoclimate Model Working Group has been to use the fully coupled CSM for scientific questions of relevance to the broad paleoclimate and climate change communities. Multihundred year simulations for present-day and pre-industrial trace gas forcing have been completed with annual average, global surface temperatures 1.3°C cooler in the pre-industrial simulation compared to the present-day simulation. Fully coupled CSM simulations have also been completed for the two Paleoclimate Modeling Intercomparison Project (PMIP) time periods, the mid-Holocene (6000 years before present), and the Last Glacial Maximum (21,000 years before present). The mid-Holocene simulation responds to changes in the latitudinal and seasonal distribution of incoming solar radiation caused by Milankovitch orbital variations with delayed sea-ice formation during the fall. The Last Glacial Maximum simulation, done in collaboration with the University of Wisconsin, simulates changes in the ocean thermohaline circulations consistent with proxy data. Fully coupled CSM simulations have explored deep-water source regions during the warm Cretaceous climate (80 million years ago) when the continental configuration was much different and atmospheric levels of CO_2 were much higher than present.

Over the next five years, the priorities of the Paleoclimate Model Working Group are threefold. The first priority is to provide a measure of decadal-to-centennial variability associated with atmosphere-ocean-ice-biosphere variations, pulses of volcanism, and solar irradiance changes. The range and nature of climate variability will be explored for the last 500 years by forcing the CCSM with reconstructed time series of the forcing mechanisms and comparing the results to proxy records (e.g., tree rings, corals, historical accounts, etc.) of climate change that supplement the instrumental record of climate observations. In earlier millennia, changes in forcing mechanisms (orbital, CO_2) were larger. CCSM simulations for time periods during the last glacial-interglacial cycle are needed to understand changes in the natural variability and the stability of the climate system caused by large changes in base state climate.

The second priority is to explore explanations of abrupt transitions in climate recorded in the ice cores and monsoon record. Ice core records in Greenland and Antarctica suggest that some regions underwent dramatic climate shifts in as little as 5 to 10 years as the climate warmed from the Last Glacial Maximum. Coupled CCSM simulations can establish possible triggering mechanisms and the modes of teleconnection, atmosphere and ocean, between regions remote from the forcing.

The third priority is to investigate processes responsible for the first-order changes of climate that have occurred over the last 600 million years. Over the last 600 million years, the climate of the Earth has varied from times of extensive continental glaciation, when ice sheets reached as far equatorward as 40° latitude, to times with little or no ice, when alligators and turtles lived near the poles. Proposed mechanisms include variations in atmospheric CO_2 and methane levels, changes in the geography and elevation of the continents and the ocean bathymetry, and the evolution of vegetation and the interactions of these mechanisms with orbital forcing.

Key short-range projects to be undertaken are the climate of the 17th-18th-19th-20th centuries (CSENT), glacial-interglacial climates and abrupt change, and warm climates of the last 100 million years.

a. Climate of the 17th-18th-19th-20th Centuries (CSENT). Comprehensive evaluation of the natural (non-anthropogenically-forced) annual, decadal, and centennial variability of the model is needed to understand the detailed paleoclimatic database compiled within the research community. The climate of the 20th century does not represent the complete range of the climate system's extremes, persistence, and decadal-to-centennial variability. Ensembles of coupled CCSM simulations will allow evaluation of the patterns, ranges, and proposed causes of decadal-to-centennial variability and the coupling of the interlinked systems of ice, atmosphere, ocean, and biosphere in this response. Reconstructed time series of climatic forcing (solar variability, volcanic activity) for the last 500 years are being evaluated. This project's milestones will include a coupled CCSM baseline simulation with no anomalous external forcing followed by simulations forced with reconstructed solar variations, volcanic activity, and anthropogenically induced atmospheric CO_2 growth, aerosol loading, and land-use change.

b. Glacial-Interglacial Climates and Abrupt Change. Analyses of ice, ocean, and lake cores have documented that the climate system has fluctuated dramatically on decadal-to-centennial time scales over the last 130,000 years. These signals in some cases appear to have a global signature. Meltwater impulses from the large Northern Hemisphere ice sheets as the climate warmed from the Last Glacial Maximum to the start of the Holocene (10,000 years ago) have been proposed as a possible causal mechanism of these major abrupt changes. Significant time lags suggest that decadal-to-centennial oscillations triggered by an impulse may have to be invoked to explain the record of change. Abrupt reorganizations during the Holocene have been hypothesized to be linked to Antarctic climate changes. We will complete a suite of simulations including idealized simulations, exploring coupled sensitivity to Arctic and Antarctic meltwater impulses and simulations to investigate three specific time periods and cycles: the early to mid-Holocene transition at 8000 years before present, the Bolling-Allerød (the abrupt onset of a warm interval about 15,000 years ago), and the Younger Dryas (a return to much colder conditions in the North Atlantic and Europe about 11,000 years ago). In the future, faster versions of the CCSM coupled with faster computers will permit transient simulations over several millennia.

c. Warm Climates of the Last 100 Million Years. Earlier periods of warmth are of great interest for the global change problem. Coupled CCSM simulations will answer questions on the nature of the ocean overturning and the role of ocean heat transport in explaining these warm climates. Initially, the CCSM will be applied to ice-free, globally warm periods during the Cretaceous (66–144 million years ago) and the early Paleogene (~60–50 million years ago), during which times there is evidence for abrupt, extreme warming events, and to the global cooling that occurred in the late Miocene and Pliocene—about the last 10 million years. During this latter period, the Antarctic ice sheet reached full development, a Greenland ice sheet developed, Arctic sea ice expanded, and glacial-interglacial cycles commenced. Previous work suggests that mountain/plateau uplift, CO_2 lowering (possibly related to major changes in chemical weathering and the carbon cycle), and changes in ocean gateways all played roles in these developments.

5. Climate Variability

The CCSM Climate Variability Working Group (CVWG) exists to encourage and facilitate the use of the CCSM and its component models for the study of climate variability on seasonal-to-centennial time scales. This problem is of intrinsic interest but is also of paramount importance for detecting anthropogenic climate change, attributing its causes, and projecting its future course. Previously, this working group had been separated into two parts, seasonal-to-interannual and decadal-to-centennial. However, we believe the issues of climate variability are better studied by a working group interested in variability over all time scales. The data sets required to understand these phenomena are provided by runs of the CCSM and its component models for periods from two decades to 1,000 years in length. Large ensembles of such runs are extremely desirable. Progress in understanding climate variability can be made by analyzing the results of experiments that have already been carried out. However, the CVWG will also design and carry out a large suite of experiments to isolate and study specific phenomena. The group will also contribute to the CCSM development by identifying the strengths and weaknesses of the model, particularly with regard to its applicability to the decadal-to-centennial time scales, and will assist in developing a science-friendly diagnostic interface between the CCSM and the user community.

Because of the model inadequacies listed in the first paragraph of Section III, the CVWG plans to sponsor a set of experiments directed towards answering specific scientific questions for the use of the community. The order of priority for these experiments over the next two years is:

a. <u>Tropical Pacific SST Mixed-Layer Integration; run of 200 years</u>. This experiment will use the CCM forced by observed SSTs in the tropical Pacific and coupled to a slab ocean model elsewhere, with spatially and seasonally varying slab depth. The purpose of this integration is to capture the effect of oceanic mixed-layer feedbacks on atmospheric variability, while still representing the strong air-sea coupling in the tropical Pacific. In particular, this configuration will better represent the temporal persistence of midlatitude and tropical Atlantic atmospheric variability.

b. <u>"Perfect Model" Atmospheric Model Intercomparison Project (AMIP)-Type Integration; run of 100 years</u>. This experiment will use the CCM forced by SSTs from a coupled CCSM integration. It will answer the question of whether AMIP-type atmospheric GCM integrations using specified SSTs can reproduce the variability of a coupled model in a "perfect model" context.

c. <u>High-Resolution (approximately T85) AMIP-II Ensemble; 5 to 10 runs of 20 years</u>. This experiment will use a higher-resolution ensemble of CCM integrations forced globally by observed SSTs. This suite of integrations will study how the variability simulated by the CCM is affected by resolution. Of particular interest are the extratropical response to the El Niño-Southern Oscillation (ENSO) and local air-sea interaction in the tropical Atlantic.

d. <u>CCM Integrations Using the Hadley Centre Global Sea-Ice and SST Climatology (GISST4) Data Set; 5 runs of 100 years</u>. This experiment includes an ensemble of integrations to be used for comparisons with other modeling groups, which are planning a similar set of integrations.

e. Extended Climatological SST Integration; run of 800 years. This experiment will be run using the latest version of the model and will extend the climatological annual cycle of the CCM from 200 years to 1,000 years. This long integration will provide a sufficiently large data set for an analysis of the statistical properties of the model's internal atmospheric variability.

The CVWG will make suggestions as necessary concerning the design of the diagnostic models and packages that are being developed by the component model working groups.

The tropical atmosphere's response to SST forcing has been demonstrated to be deterministic in the conventional model twin experimental design, and recent evidence suggests that seasonal mean midlatitude anomalies forced by tropical SSTs are predictable. Similarly, it is well recognized that the MJO and ENSO are inherently predictable over at least a quarter of their lifetimes. The deterministic reproduction of the low-frequency phenomena is vital to developing our confidence in the CCSM's ability to accurately replicate the slow physical adjustments inherent in climate variability and climate change. The dominant climate signal at interannual time scales is ENSO variability. We have learned much about the nature of ENSO, but there are still some fundamental outstanding issues. Of particular interest are the relationship of ENSO to the annual cycle, the quasi-biennial and decadal variability of ENSO, and the global response to ENSO. These issues involve, indirectly or directly, ENSO's intrinsic predictability, the mechanisms responsible for its irregular behavior over time, and its coupling to the Asian monsoon and global circulation.

It is essential to explore model sensitivities to variations in how physical processes in both the atmosphere and ocean are treated. The processes that we currently think are most likely to affect the tropical annual cycle and variability of the ocean and atmosphere, and that we will scrutinize first, are those responsible for redistribution in the vertical heating in the atmosphere, heat flux into the ocean, and vertical mixing in the ocean. For example, coupled simulations with smaller background vertical diffusivity in the ocean component have larger El Niño amplitude, especially in the Niño3 region. This is directly related to an improved simulation of the mean thermal structure of the equatorial upper ocean and a more intense Pacific thermocline due to the reduced vertical mixing. Figure 8 shows Niño3 amplitude (top) and Niño4 amplitude (bottom) versus ocean model background vertical diffusivity for a coupled simulation with versions of the CSM and the Parallel Climate Model (PCM). The solid lines represent Niño3 and Niño4 amplitudes for the observations from 1950-1979 and 1950-1998.

It is also important to investigate the role of moisture stored in or depleted from the soil in sustaining anomalous summertime precipitation regimes. Investigations with coupled models of variability during the summer season will compare the simulated seasonal climates of integrations that are initialized with climatological values of vegetation and soil moisture with those that use more realistic vegetation and soil moisture. This will provide an assessment of the usefulness of extratropical continental surface forcing in seasonal prediction.

Top priorities are:

- to diagnose and suggest possible avenues to improve the component models so that the full CCSM can better simulate coupled atmosphere-ocean variability on interseasonal, seasonal, and interannual time scales. This will include a diagnostic analysis of the coupled model and its components with respect to ENSO, monsoon, and tropical Atlantic variability.

- to use the component models for predictability and sensitivity studies to further understanding of the nature and predictability of interannual variations of the climate system and their importance in the dynamics of longer-term climate variations and climate response to external forcing.

- to participate in national and international model intercomparison projects to diagnose simulated climate variability and to carry out seasonal and interannual hindcasts.

6. Climate Change and Assessment

The CCSM Climate Change and Assessment Working Group (CCAWG) was formed in early 2000 to coordinate climate change simulations by the CCSM and those supported by the U.S. Department of Energy's (DOE) Climate Change Prediction Program (CCPP). Work is proceeding on using the same model components in the CCSM and the DOE-supported Parallel Climate Model (PCM), so that the models will essentially be the same for climate change simulations. We plan to have a version of the merged model by 2001. The merged model is likely to be executed on available computers at NSF-supported centers and at DOE laboratories. Over the next five years, there will be a need for a series of climate change ensemble simulations that will be part of coordinated studies by the IPCC, the U.S. National Assessment, and the WCRP's Climate Variability and Predictability program (CLIVAR). Furthermore, we expect to be part of intercomparisons with other national and international modeling groups. As the models continue to develop and become more realistic, we expect to contribute to special simulations related to the missions of NSF and DOE.

This is a new working group and detailed plans will be discussed at the Breckenridge workshop in June 2000. Our general plan is:

- to design and carry out climate change simulations. For example, help specify the climatic forcing to use in the simulations, such as the changes in greenhouse gases, aerosols, solar variability, and volcanic activity.

- to plan and coordinate for statistical analysis of the simulations with an emphasis on detection of climate change.

- to work with other CCSM working groups to develop model components and a fully coupled climate model system that is suitable for climate change simulations. Some simulations should be conducted with higher-resolution ocean and atmospheric components than those of the nominal CCSM version to better capture regional climate change.

- to advise on what model data will be made available from climate change simulations, consistent with the CCSM Data Policy. The DOE-supported simulations will have a data availability policy consistent with that of DOE CCPP. Some of the CCSM data will be archived at the NCAR Scientific Computing Division (SCD) and some at DOE's Program for Climate Model Diagnosis and Intercomparison (PCMDI). We plan to use the Internet for data sharing and access to allow a larger group of scientists to be involved in climate change modeling research.

Note that performing ensembles of simulations takes a great deal of computer time and conducting such simulations often requires many months to years.

IV. Community Involvement and Outreach

A. Community Involvement and Outreach

The involvement of a broad community of scientists interested in climate simulation has been a high priority of the CSM project from its inception. The original CSM proposal called for the free distribution of the CSM code, documentation, and results of major simulations. Furthermore, the proposal called for convening a workshop in the summer of 1996 to promote the involvement of the community in the further development of the CSM, as well as the analysis of existing simulations and application of the model to new problems.

Extensive community involvement started with that workshop; 118 people attended, most from outside NCAR. The initial release of the CSM was announced at the workshop, and many encouraging results were shown. However, the most important outcomes of the workshop were the adoption of the community-based governance structure for the CSM and the establishment of several working groups with broad participation. CCSM workshops are now held annually, with participation increasing each year (see table below). There are currently nine CCSM working groups established under the Scientific Steering Committee, each with co-chairs from NCAR and one or more other institutions to foster collaboration.

CSM Meetings	**Date of Meeting**	**Venu Meeti**
CMAP Scientific Advisory Council	2–3 March 1995	
CMAP Scientific Advisory Council	7–8 December 1995	Bould
1st Annual CSM Workshop	**15–17 May 1996**	Breck
CSM Scientific Steering Committee	5 September 1996	Bould
Polar Climate Workshop	6–7 January 1997	Bould
Atmosphere Model Working Group	14–15 January 1997	Bould
CMAP Scientific Advisory Council	21 January 1997	Boul
Joint CMAP Scientific Advisory Council & CSM Scientific Steering Committee	22–23 January 1997	Bould
Joint Seasonal-to-Interannual WG & Decadal-to-Centennial WG	7–8 May 1997	Bould
CSM Scientific Steering Committee	23 June 1997	Breck CO
2nd Annual CSM Workshop	**24–26 June 1997**	Brecke
CSM Scientific Steering Committee	30 Sept–1 Oct 1997	Bould
CSM Scientific Steering Committee	27 January 1998	Bould
Paleoclimate Model WG	17–18 February 1998	Bould
Land Model WG	19–20 February 1998	Bould
Atmosphere Model WG	2–3 March 1998	Bould
Data Management Workshop	7 May 1998	Bould
3rd Annual CSM Workshop	**22–24 June 1998**	Breck
CSM Scientific Steering Committee	22 June 1998	Breck
Joint CMAP Scientific Advisory Council, CSM Scientific Steering Committee, & CSM Working Group Co-Chairs	25 June 1998	Breck
CMAP Scientific Advisory Council	25 June 1998	Breck
Biogeochemistry WG	20 August 1998	Denv
Joint Ocean Model WG, Polar Climate WG, Paleoclimate Model WG	19–20 January 1999	Bould
CSM Scientific Steering Committee	10–11 February 1999	Bould
Joint Atmosphere Model WG, Natural Variability WG and Seasonal-to-Interannual WG	12–14 April 1999	Bould
*CSM Advisory Board	29–30 April 1999	Washi
4th Annual CSM Workshop	**22–24 June 1999**	Brec CO
Sea Ice Planning Meeting	27–28 September 1999	Bould

Land Model WG	8–9 November 1999	COL
Software Engineering Meeting	10–11 November 1999	Bould
CSM Advisory Board	30 November 1999	Washi
**CCSM Scientific Steering Committee	6–7 January 2000	Bould
Joint Ocean Model and Polar Climate WGs	18–19 January 2000	Bould
Data Processing and Visualization Workshop	31 Jan–4 Feb 2000	Bould
Joint Seasonal-to-Interannual and Decadal-to-Centennial WGs	3–4 February 2000	COL (Maryl
Biogeochemistry WG	28–29 March 2000	Bould
CCSM Scientific Steering Committee	12 May 2000	Bould
CCSM Scientific Steering Committee	26 June 2000	Brec CO
5th Annual CCSM Workshop	**27–29 June 2000**	Breck
Joint Scientific Steering Committee/CCSM Advisory Board/Working Group Co-chairs	30 June 2000	Breck CO

*CSM Advisory Board changed its name from CMAP Scientific Advisory Council.
**CSM changed its name to CCSM (Community Climate System Model)

B. Free Availability of CCSM Code and Output Data

The complete CSM software was first released on the World Wide Web in June 1996. CSM-1.1 was released in the fall of 1996. CSM-1.2 was released on the Web in July 1998. This code implemented the same algorithms as in CSM-1.1 but with considerable improvements to the code, build procedures, and run scripts. One notable improvement was that CSM-1.2 treated all component models (sea ice, ocean, atmosphere, and land) as separate entities. A full set of simple, noninteractive, data set–reading component models was also provided. This code could be run on NCAR Cray machines and also could be ported to other architectures and machines outside NCAR.

The CCSM component models' source code and documentation are freely available from the CCSM Web site at http://www.cgd.ucar.edu/csm/models. Output data from the primary CCSM simulations are available both on the Web and from the NCAR Mass Storage System. Both the bulk raw model output data and postprocessed collections of time series of individual variables are distributed.

C. Community Use of CCSM

We have provided instructions for using and running the CCSM and CCSM data to NCAR scientists, non-NCAR scientists, and other NCAR climate assessment/modeling teams. In some time-critical situations, we have extracted CCSM data and sent them to non-NCAR researchers.

Appendix A
Management Plan

I. Management Structure for the Community Climate System Model

A. Project Goals

The primary goal of the Community Climate System Model (CCSM) project is to develop a state-of-the-art climate model and to use it to perform the best possible science to understand climate variability and global change. We will strive to build a CCSM community of users who are interested in participating in this project. To promote meaningful participation of those interested, the following management structure is in place.

B. CCSM Advisory Board

The CCSM Advisory Board (CAB) will serve as an advisory committee reporting to the CCSM Scientific Steering Committee, NSF Program Director, NCAR Director, and UCAR President. The CAB will meet regularly (approximately twice per year) and listen to the accomplishments in CCSM development and use. They will issue reports and make recommendations to the leadership of CCSM and to the managers mentioned above. The members of the CAB will have limited terms and rotate off the committee regularly. CAB members will be selected jointly by the NSF Program Director, NCAR Director, and UCAR President. Appointments to the committee will be made by the UCAR President. Membership in the CAB will come from NCAR staff, university faculty and staff, staff members of national laboratories, and scientists from foreign universities, laboratories, and centers.

C. CCSM Scientific Steering Committee

The CCSM Scientific Steering Committee (SSC) will provide scientific leadership for the CCSM project, including oversight of activities of working groups, coordination of model experiments, decision making on model definition and development, encouragement of external participation in the project, and promotion of CCSM with NSF and other agencies, as appropriate. Also, it will provide information to the CAB, as requested, on the functioning and progress of the CCSM. Some specific functions of the CCSM SSC will be:

- to promote and sustain model development to keep the CCSM at the state of the art.

- to identify and encourage work in those areas needed for the progress of CCSM.

- to set priorities and make recommendations on model development and use.

- to develop policies for the use of the model for major experiments and the use of model-generated data sets.

- to determine what working groups should be organized and to oversee the activities of these working groups, so that redundancy is reduced and communication is maximized. The SSC will appoint a chair or co-chairs for each working group, drawing on scientists from the CCSM community. These appointments will be for a limited term. Reappointment is possible. Rotation of chair positions is expected.

- to decide which components and/or parameterizations should be included in future versions of CCSM. Proposals for new components and/or parameterizations should come from the appropriate working groups, together with appropriate reasons for the recommended changes and documentation of the results. The SSC will decide by consensus, if possible, but otherwise by majority vote whether to accept the recommendation, reject the recommendation, or ask for further study or documentation.

- to write proposals for allocation of computer time from the Climate Simulation Laboratory for official CCSM activities. The SSC will solicit input from the co-chairs of working groups and write a unified proposal encompassing all official CCSM activities. Upon receiving the total allocation, the SSC will allocate computer time to the co-chairs of the working groups, who will then allocate their time to participants.

- to hold regular management meetings, at least two per year, to listen to reports from CCSM scientists and working group co-chairs, to consider proposed modifications to the model, and to perform those tasks necessary for the progress of CCSM.

- to hold regular scientific meetings, or workshops, approximately one per year, so that the entire CCSM community will be informed about the state of the model development and of applications of the model for various purposes.

The primary goal of the CCSM SSC and the CCSM Working Groups, which will be defined below, is to promote collaboration and efficient development of the CCSM. The CCSM SSC and CCSM Working Groups will encourage smaller activities to work in cooperation with larger CCSM projects, but they will not seek to manage or prioritize activities requiring only modest resource use. Scientists should be encouraged to participate in the CCSM, so they have the advantage of convenient access and ability to contribute to a state-of-the-art climate system model that is well documented and validated. They will also have the advantage of some community support resources and an established infrastructure.

The CCSM SSC members will consist of the Director of NCAR's Climate and Global Dynamics (CGD) Division, who will serve as Chairman of the CCSM SSC, plus

eight additional scientists. Initially, four will be NCAR staff members and four will be from the university and national laboratory community. There will be at least four non-NCAR members on this committee. The CCSM SSC members will be appointed by the UCAR President for terms of two years, with the possibility of reappointment. (Half of the first group appointed will be appointed for one-year terms, so that only half of the CCSM SSC rotating membership will be appointed in any year.) Rotation of SSC membership is expected.

CCSM SSC decisions will be made by consensus, if possible, but otherwise by majority vote. The CCSM SSC will strive to develop and maintain a harmonious, cooperative working arrangement among the various scientists working on the CCSM.

D. <u>CCSM Working Groups</u>

The detailed work on various aspects of CCSM will be done in working groups. These working groups will consist of scientists who come together to work on topics on which they share common interest. These groups will be inclusive. The working groups should allow scientists to participate in cooperative research to minimize unnecessary duplication and competition, so that improvements to CCSM can be made and so that high-quality uses of the CCSM can be achieved. The working groups will present their research and their recommendations to the CCSM SSC. The SSC desires that the working groups reach consensus on their recommendations for changes in the model or about allocations for computer time for major experiments, but if they cannot, the CCSM SSC will have the authority to make decisions on which recommendations to accept or reject. The SSC may also call for further research before any decision is made.

Working groups may be primarily interested in diagnostic activity, use of the model for various scientific experiments, model development, or some combination of interests. Examples of working groups are Atmosphere Model Working Group, Ocean Model Working Group, Land Model Working Group, Paleoclimate Model Working Group, Polar Climate Working Group, Climate Change and Assessment Working Group, Climate Variability Working Group, and Biogeochemistry Working Group. The SSC will organize other working groups as needed and appoint the co-chairs.

E. <u>CCSM Program Office</u>

A small CCSM Program Office will be maintained at NCAR/CGD. This office will coordinate CCSM SSC meetings, CAB meetings, and CCSM Working Group meetings.

A budget will be available to support travel, short-term visits, workshops, and other costs associated with the operation of the CCSM SSC, CAB, and Working Groups. The CCSM SSC and its designated representative will have the authority to determine priorities for the expenditure of funds in the Program Office.

II. Management Lists

Membership lists are included in this section for the CCSM Scientific Steering Committee (SSC), CCSM Advisory Board (CAB), and CCSM Working Group Co-Chairs. Each list is available from the CCSM Home Page on the Web at http://www.cgd.ucar.edu/CSM. The SSC and CAB lists are under Project Management and the CCSM Working Group Co-Chair list is under Working Groups.

CCSM Scientific Steering Committee (SSC) Members

Dr. Maurice L. Blackmon, NCAR, Chair
Dr. Byron Boville, NCAR
Dr. Robert Dickinson, Georgia Institute of Technology
Dr. Peter Gent, NCAR
Dr. Jeffrey Kiehl, NCAR
Dr. Richard E. Moritz, University of Washington
Dr. David Randall, Colorado State University
Dr. Jagadish Shukla, Institute for Global Environment & Society
Dr. Susan Solomon, NOAA

Ex-Officio Members

Dr. Anjuli Bamzai, NSF
Dr. Jay Fein, NSF

CCSM Advisory Board (CAB) Members

Dr. Richard A. Berk, UCLA
Dr. Francis P. Bretherton, University of Wisconsin-Madison
Dr. Michael Ghil, UCLA
Dr. Isaac M. Held, Geophysical Fluid Dynamics Laboratory/NOAA
Dr. Tony Hollingsworth. European Centre for Medium-Range Weather Forecasts
Dr. Robert Malone, DOE/Los Alamos National Laboratory
Dr. Steven Running, University of Montana
Dr. Ed Sarachik, University of Washington, Chair
Dr. Albert Semtner, Jr., Naval Postgraduate School
Dr. Max J. Suarez, NASA/Goddard Space Flight Center
Dr. Kevin Trenberth, NCAR
Dr. Stephen E. Zebiak, International Research Institute for climate prediction (IRI)

Ex-Officio Members

Dr. Richard Anthes, UCAR
Dr. Maurice L. Blackmon, NCAR
Dr. Jay Fein, NSF
Dr. Robert Serafin, NCAR

CCSM Working Group Co-Chairs

Atmosphere Model
Dr. James Hack, NCAR
Dr. David Randall, Colorado State University

Ocean Model
Dr. Peter Gent, NCAR
Dr. Michael Spall, Woods Hole Oceanographic Institution

Land Model
Dr. Gordon Bonan, NCAR
Dr. Robert Dickinson, Georgia Institute of Technology

Polar Climate
Dr. Richard E. Moritz, University of Washington
Dr. Elizabeth Hunke, DOE/Los Alamos National Laboratory

Paleoclimate
Dr. Bette Otto-Bliesner, NCAR
Dr. John Kutzbach, University of Wisconsin-Madison
Dr. Lisa Sloan, University of California, Santa Cruz

Climate Variability
Dr. Joseph Tribbia, NCAR
Dr. Jagadish Shukla, Institute for Global Environment & Society
Dr. R. Saravanan, NCAR
Dr. J. Hurrell, NCAR
Dr. Edwin K. Schneider, Center for Ocean-Land-Atmosphere Studies

Biogeochemistry
Dr. Scott Doney, NCAR
Dr. Inez Fung, University of California, Berkeley

Climate Change and Assessment
Dr. Warren Washington, NCAR
Dr. Gerald Meehl, NCAR
Dr. Karl Taylor, Program for Climate Model Diagnosis and Intercomparison (PCMDI)

Software Engineering
Dr. Richard Rood, NASA Goddard Space Flight Center
Ms. Cecelia DeLuca, NCAR

III. CCSM SSC Terms of Reference

A. Charge

The CCSM Scientific Steering Committee (SSC) will provide scientific leadership for the Community Climate System Model (CCSM) project, including oversight of activities of working groups, coordination of model experiments, decision making on model definition and development, writing proposals for computer time to the Climate Simulation Laboratory and elsewhere, if appropriate, encouragement of external participation in the project, and promotion of CCSM within NSF and other agencies, as appropriate. Also, it will provide information to the CCSM Advisory Board (CAB), as requested, on the functioning and progress of CCSM.

B. Membership

The CCSM Scientific Steering Committee (SSC) will consist of nine members, including at least four scientists not employed at NCAR, and the Director of NCAR's Climate and Global Dynamics Division, who will serve as Chair. The members will represent broad scientific disciplines related to earth-system modeling and will serve terms of up to two years in duration. Reappointment is possible. Rotation of SSC membership is expected.

C. Appointment of Members

The members of the CCSM SSC will be appointed by the UCAR President after consultation with the Director of the NSF-ATM Climate Dynamics Program and the Director of NCAR.

D. Meeting Frequency

The CCSM SSC will meet at least two times a year, or more often as needed.

IV. CCSM CAB Terms of Reference

These terms of reference apply to the CCSM Advisory Board (CAB), which replaced the Climate Modeling, Analysis and Prediction (CMAP) Scientific Advisory Council (SAC) as described in the SAC Terms of Reference dated 28 April 1997.

A. Background

NSF's CMAP budget initiative has evolved to support two components, a coordinated NCAR-university Community Climate System Model (CCSM) activity and individual university modeling research projects. It is the coordinated CCSM component of CMAP that requires oversight and guidance. Furthermore, CCSM has matured and improved over the past few years and now has potential to serve multiagency needs. For these reasons, the present CMAP advisory body, the CSMP Scientific Advisory Council (CSAC), is being reconstituted as the CCSM Advisory Board (CAB), an advisory body for CCSM with members representing a broad spectrum of the multiagency U.S. Global Change Research Program (USGCRP).

B. Definition of CMAP

CMAP (Climate Modeling, Analysis and Prediction) is a NSF program supporting research in climate system model development, simulation and prediction, validation, error estimation, and assessment of predictability. CMAP is a part of NSF's focused USGCRP.

C. Definition of CCSM

CCSM (Community Climate System Model) is a focussed community effort led by NCAR for the development and analysis of comprehensive climate system models. It is a key component of CMAP, and is supported by CMAP, with complementary support from NSF base funding at NCAR and from other agencies.

D. Definition of CCSM Scientific Steering Committee (SSC)

The CCSM SSC provides scientific leadership and oversight for the CCSM project, including management of working groups, coordination of model experiments, decision making on model definition and development, encouragement of external participation in the project, and promotion of CCSM within NSF and other agencies, as appropriate. It also provides information to the CCSM Advisory Board, as requested, on the functioning and progress of CCSM.

E. Charge to CCSM Advisory Board (CAB)

To provide advice to the SSC, the Director of NCAR, the NSF-ATM Program Director, and the President of UCAR on a wide spectrum of scientific and technical activities within or involving the CCSM. The CAB should address the progress and quality of these activities, their balance, and their interactions with other closely related climate modeling and research activities, both national and international, with the ultimate aim of building a more unified modeling community to enhance progress in climate modeling. The CAB provides advice on future CCSM plans, coordinates CCSM activities with related efforts in other agencies, promotes the CCSM mission and their activities in the national and international community, and provides help in building and expanding the CCSM community.

F. Membership

The CAB consists of approximately 12 to15 scientists from the university community, NCAR, and other laboratories and institutions, as appropriate. The members represent broad scientific disciplines related to earth-system modeling and serve rotating terms of three years. The Chair of the CCSM SSC, NSF-ATM Program Director, Director of NCAR, President of UCAR, and representatives from other agencies, as appropriate, will serve as ex-officio, nonvoting members.

G. Appointment of Members

The members of the CAB will be appointed by the President of UCAR, after consultation with the Director of NSF-ATM Climate Dynamics Program, the Director of NCAR, and the Chair of the SSC.

H. Organization and Funding

The CAB will be funded through the CCSM Program Office.

I. Meeting Frequency

The CAB will meet at least once a year or more often as needed.

APPENDIX B
ACKNOWLEDGEMENTS

OTHER AGENCY SUPPORT OF CCSM

DOE/Pacific Northwest National Laboratory, Jerry Elwood and David Bader, Program Managers

- D. Randall, CSU
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- J. Hack, NCAR
- D. Williamson, NCAR
- T. Bettge, NCAR
- J. Meehl, NCAR
- J. Arblaster, NCAR

- R. Dickinson, Georgia Institute of Technology

Carbon Dioxide Research Program

- J. Weatherly, Cold Regions Research and Engineering Laboratory

NOAA Office of Global Programs (OGP), Mark Eakin, Jim Todd, and Mike Patterson, Program Managers

- D. Battisti and his students, University of Washington

OGP Climate and Global Change Program, ACCP, Jim Todd, Program Manager

- Bill Large, NCAR

OGP Climate and Global Change Program, GOALS, Ken Mooney, Program Manager

- Bill Large, NCAR

Consortium of the Ocean's Role in Climate, Ken Mooney, Program Manager

- Bill Large, NCAR

NASA BOREAS, D. Wickland, Program Manager

- G. Bonan, NCAR

SCARAB, D. Starr, Program Manger

- W. Collins, NCAR

EOS, D. Starr, Program Manager

- W. Collins, NCAR

NASA, Ken Bergman, Program Manager

- R. Dickinson, Georgia Institute of Technology

CRIEPI, S. Nishinomiya, Program Manager

- A. Kasahara, NCAR

Appendix C
List of Acronyms

ACSYS	Arctic Climate System Study
AMIP	Atmospheric Model Intercomparison Project
AMWG	Atmosphere Model Working Group

BGCWG	Biogeochemistry Working Group
CAB	CCSM Advisory Board
CCAWG	Climate Change and Assessment Working Group
CCCWG	Chemistry and Climate Change Working Group
CCM	Community Climate Model
CCPP	Climate Change Prediction Program
CCSM	Community Climate System Model
CEDAR	Coupling Energetics and Dynamics of Atmospheric Regions program
CFCs	chlorofluorocarbons
CICE	sea-ice model developed at Los Alamos National Laboratory
CLIVAR	Climate Variability and Predictability Program
CLM	Common Land Model
CMAP	Climate Modeling, Analysis and Prediction Program
CMS	Climate Modeling Section
CO_2	carbon dioxide
CRIEPI	Central Research Institute of Electric Power Industry, Japan
CRREL	Dept. of Army Cold Regions Research and Engineering Laboratory
CSENT	climate of the 17th-18th-19th-20th centuries
CSM	Climate System Model
CVWG	Climate Variability Working Group
DOE	U.S. Department of Energy
ENSO	El Niño–Southern Oscillation
EOF	empirical orthogonal function
FDM	full-depth model
FIRE-ACE	First ISCCP (International Satellite Cloud Climatology Program) Regional Experiment-Arctic Cloud Experiment
GAIM	Global Analysis Interpretation and Modeling Ocean Carbon Model Intercomparison Project
GCM	general circulation model
G-M	Gent-McWilliams parameterization scheme
GtC	gigatons of carbon
HIRDLS	high-resolution dynamics limb sounder
IGBP	International Geosphere-Biosphere Programme
IPCC	Intergovernmental Panel on Climate Change
ISCCP	International Satellite Cloud Climatology Program

KPP	K Profile Parameterization
LSM	Land Surface Model
LTE	local thermodynamic equilibrium
MACCM3	middle atmosphere version of CCM3
MJO	Madden-Julian Oscillation
MOZART	Model of Ozone and Related Trace Species
NAO	North Atlantic Oscillation
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NCOM	NCAR CSM Ocean Model
NSF	National Science Foundation
OS	Oceanography Section
PBL	planetary boundary layer
PCM	Parallel Climate Model
PCMDI	Program for Climate Model Diagnosis and Intercomparison
PCWG	Polar Climate Working Group
PMIP	Paleoclimate Modeling Intercomparison Project
POP	Parallel Ocean Program
ppm	parts per million
ppmv	parts per million by volume
QBO	Quasi-Biennial Oscillation
SCD	NCAR's Scientific Computing Division
SHEBA	Surface Heat Budget of the Arctic Ocean
SSC	Scientific Steering Committee
SSTs	sea surface temperatures
TIME	thermosphere-ionosphere-mesosphere-electrodynamics
TIMED	thermosphere-ionosphere-mesosphere-energetics-dynamics
UARS	Upper Atmosphere Research Satellite
UCAR	University Corporation for Atmospheric Research
UOM	upper-ocean model
USGCRP	U.S. Global Change Research Program
WCRP	World Climate Research Programme