Community Climate System Model Science Plan

(2004-2008)

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Table of Contents

Executive Summary

- This plan reports on what has been accomplished in the Community Climate System Model (CCSM) project since June 2000 and lays out both a short-term program for model development and improvement that promises to have immediate practical benefits, and a scenario of scientific questions that are of interest to the community that require further model development and resources.

- The CCSM program has continued to grow and develop since the original CCSM plan was released in June 2000.

- A 1000-year coupled simulation with no flux correction was completed. This simulation exhibits very little overall climate drift and thus has established a new standard for scientific credibility of climate simulation at the international level.

- Simulations of the ocean sea surface temperature at mid and high latitudes are substantially improved over the previous coupled model, Climate System Model version 1 (CSM1).

- Simulations of the extent of sea ice are remarkably close to observations in both hemispheres.

- The simulations in the tropical regions have improved in some aspects but remain a large challenge as there are differences between the fine structure of the equatorial sea surface temperatures and observations that lead to differences in ocean-atmosphere interaction and thus tropical clouds and precipitation.

- Simulations of land surface properties have eliminated the cold bias that was ubiquitous in CSM1, but there is a warm bias that is present in polar land areas in winter. This may also be a factor in the simulated low sea ice thickness.

- The variability exhibited in the 1000-year integration is considerably more realistic than in CSM1 although it remains somewhat deficient as compared to observations in the tropical regions.

- The climate sensitivity of CCSM2 is low compared to that of many other climate models. However, simulations of the past millennium show remarkable agreement with proxy reconstructions and the instrumental record of the past 100 years.

- An extensive program in applied climate modeling will be conducted using the latest version of CCSM2, including the construction of ensembles of simulations of the response of CCSM2 to projected changes in greenhouse gases and the addition of a multidimensional suite of simulations that will be useful in addressing the uncertainties in the climate projections associated with resolution and physical parameterizations.

- A vigorous research program is underway to understand the biases displayed in CCSM2 and to modify the modeling system to have the best possible climate simulation tool to conduct climate projection experiments for the Intergovernmental Panel for Climate Change (IPCC) Fourth Assessment Report.

- A major effort will be to tackle the question of how the uncertainty in climate projections is related to the limitation in the model's representation of physical and dynamical processes.

- The CCSM program will complete the implementation of a fully interactive carbon cycle within CCSM in the near future; this model will provide input to the IPCC process.

- The paleoclimate community wishes to explore much more extensively the history of Earth's climate using the CCSM, including a detailed look at the response to solar input variation in the context of other climate forcing and as to why Earth has been warmer than now for most of its history.

- An extensive survey of the scientific questions that are of interest to the CCSM scientific community has been carried out leading to the definition of major new directions for the development and use of the CCSM. These extensions of the model include the addition of more comprehensive biogeochemical processes, addition of homogeneous and heterogeneous atmospheric chemical processes, and addition of fully interactive atmospheric aerosol processes.

I. Scientific Objectives of the Community Climate System Model Program

The scientific objectives of the Community Climate System Model (CCSM) program are as follows:

- Develop and continuously improve a comprehensive climate modeling system that is at the forefront of international efforts to understand and predict the behavior of Earth's climate.

- Use this modeling system to investigate and understand the mechanisms that lead to interdecadal, interannual, and seasonal variability in Earth's climate.

- Explore the history of Earth's climate through the application of versions of the CCSM suitable for paleoclimate simulations.

- Apply this modeling system to estimate the likely future of Earth's environment in order to provide information required by governments in support of local, state, national, and international policy determination.

The CCSM program is a component of the overall U.S. Climate Change Science Program (CCSP). It is a large project involving a large community of scientists and stakeholders in design, construction, evaluation, and use of the ultimate product, the CCSM. The program is a high-priority activity within the Climate and Global Dynamics (CGD) Division of the National Center for Atmospheric Research (NCAR). It provides the infrastructure and support mechanisms necessary for university scientists and other collaborators to contribute to the building of a common climate modeling system, as well as to use the modeling system to address scientific questions about Earth's climate, past, present, and future. Program priorities and decisions are based on scientific peer review and scientific consensus, and the results of the program are open to all. It provides the opportunity to support diversity in the approach to both an outstanding intellectual challenge and a major societal issue. The program also has a mission to foster the creative involvement of university researchers and students in the subject area and thus contribute to the development of highly trained people. The program is a complement to the other major modeling programs in the CCSP that are specifically oriented toward a government mission to provide decision-support information.

II. Brief History of the CCSM Program

In 1993 a small group of scientists within the CGD Division of NCAR began meeting to discuss the possibility of building a new, comprehensive, coupled climate model. This group evolved into the CMAP (Climate Modeling, Analysis, and Prediction Scientific Advisory Council). The basic agreement was that the model would be composed of existing component models in use within the division, that these models would be coupled together through a separate module or coupler, and that no flux corrections or flux adjustments would be used to alleviate biases within the coupled system. The fully coupled model was developed in collaboration with scientists in CGD's Climate Modeling and Oceanography Sections, with interest from other scientists in the division to further develop the model to include biogeochemical processes.

After discussions with the director of CGD, the director of NCAR, and the president of the University Corporation for Atmospheric Research (UCAR), a proposal was written to the National Science Foundation (NSF) that outlined the need for such a new coupled model. Development of the coupled model began in 1994. In 1996, the first coupled simulation was carried out, and this initial simulation showed no indication of the surface climate drift exhibited in all previous coupled simulations carried out by the international community. This was a significant accomplishment in the science of coupled models.

The first CCSM community workshop was held in Breckenridge in May 1996. Results from the simulation of a 300-year control run were presented at the meeting. It was recognized that further development of the CCSM would require a more organized management structure, so the CCSM Scientific Steering Committee (SSC) was formed shortly after the workshop. At this time various working groups were formed to provide forums for model development and application activities. Since this time the CCSM annual workshop has become one of the most comprehensive climate modeling meetings in the United States. Attendance at the workshop has grown considerably over the years (Figure 1) from 100 to close to 300 attendees.

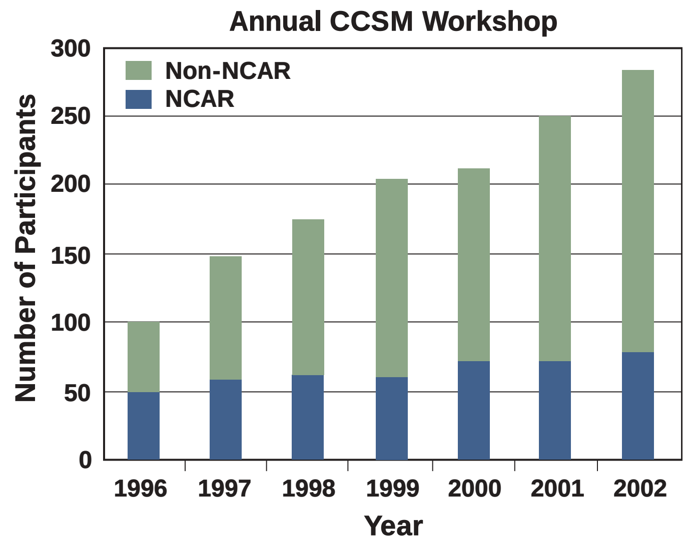
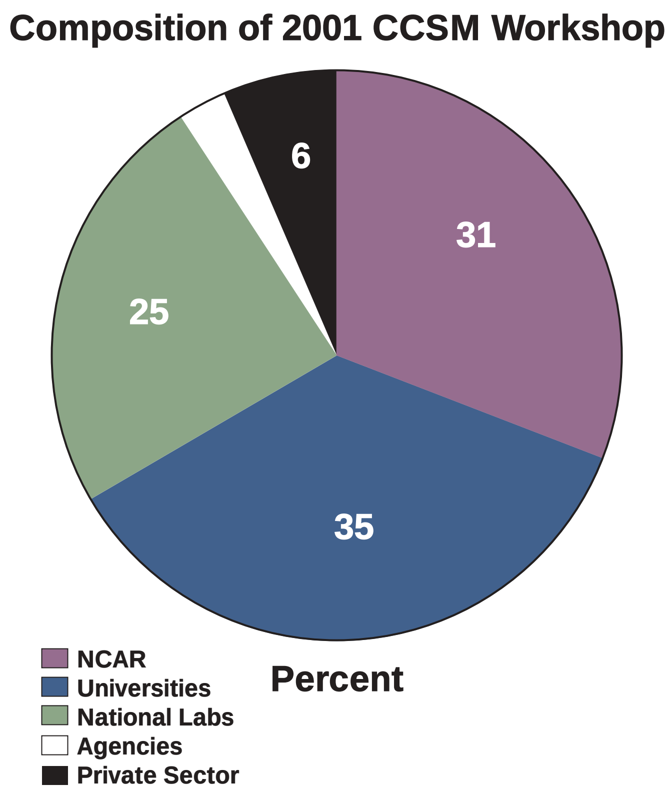


Figure 1. Number of participants at the annual CCSM workshop, with NCAR participants (blue) and non-NCAR participants (green).

After the release of the first version of the Climate System Model, CSM1, to the community in 1996, it was recognized that development of the model would require expertise in a wide range of disciplines. Also, members of the greater climate community were interested in contributing to the development of the CCSM. An indication of the diverse community for this activity is shown in Figure 2.

Working groups were formed in areas of the component models (atmosphere, ocean, land, and polar processes) and in areas of diagnosis (climate variability) and applications (paleoclimate, climate change). Development of a biogeochemistry component required the formation of a working group in that area, and finally the complexity of the software composing the model reached a point where a working group on software engineering was necessary. At present these nine working groups make up the working-level structure of the CCSM (Figure 3). These working groups report to the CCSM SSC, whose membership is composed of NCAR, university, and national laboratory scientists. More detailed information on the responsibilities and activities of the various bodies of the CCSM project can be obtained at the Web site, www.ccsm.ucar.edu. Up until 2001, the director of the CGD Division was the chairman of the SSC and thus managed all aspects of the CCSM. The day-to-day

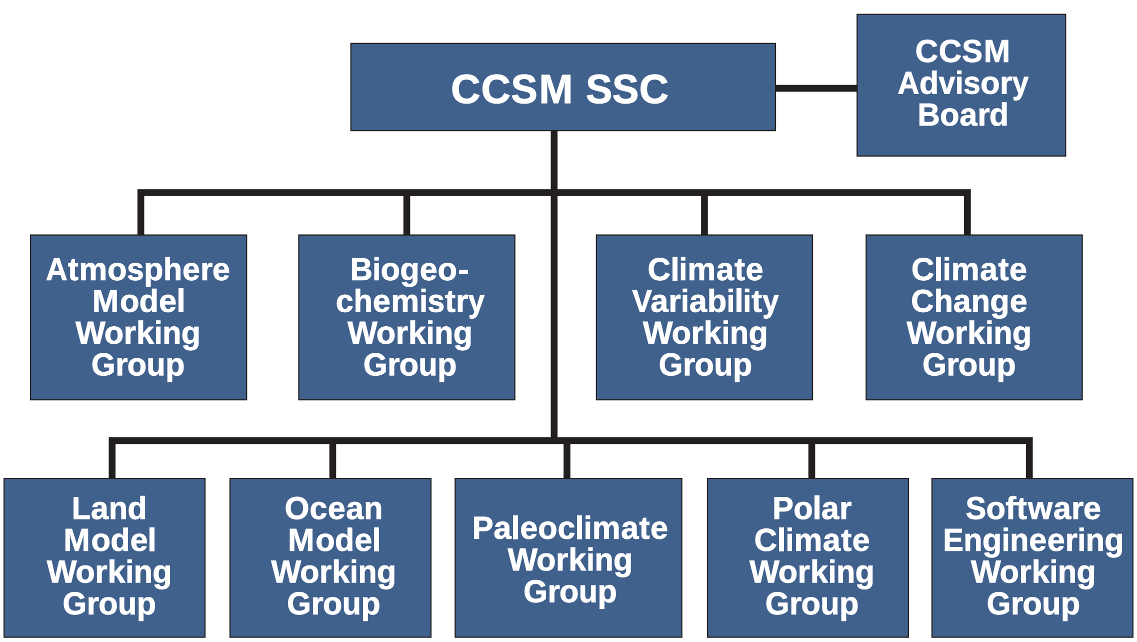
Figure 2. Attendance at the 2001 CCSM workshop, in percent.



development work was carried out by two scientific co-chairs. In June 2001, it was decided that all of these responsibilities would be transferred to the new chairman of the SSC. The chairman of the SSC was now given the responsibility to direct the day-to-day operations of the CCSM, coordinate activities of the SSC, and report the status of the CCSM program to the president of UCAR, the director of NCAR, the head of the Climate Dynamics Program at NSF, the head of the climate modeling program at the U.S. Department of Energy (DOE), and the CCSM Advisory Board (CAB). The CAB was formed to provide advice to the SSC, the NSF management, the president of UCAR, and the director of NCAR on the status of the CCSM program.

The first CCSM plan was published in June 2000 and laid out both the scientific objectives of the program and the overall management plan. It was envisaged that the primary task of the project was to upgrade the whole model to be competitive with the best models on the international level. This involved an intense development effort over the next two years, culminating in the public release of the CCSM2 in May 2002. This plan reports on the progress made in the CCSM program since June 2000 and defines the prospects for the further development of the program.

Figure 3. Organizational structure of the CCSM working groups.



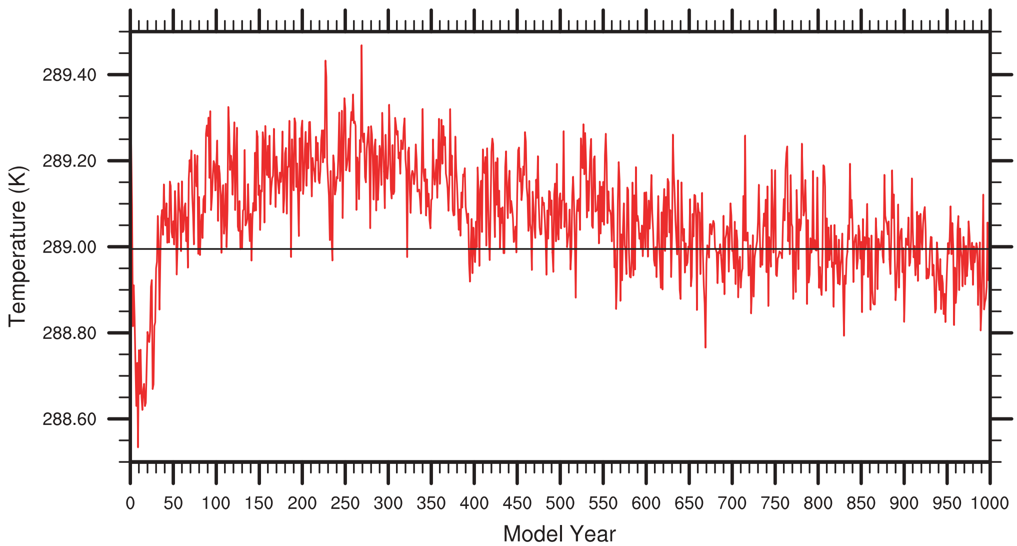
III. Scientific Accomplishments of CCSM2

The period from June 2000 to June 2002 was very intense in terms of model development. There was a strong desire to make modifications to the first version that would incorporate better representations of the physical processes, take advantage of the scientific community's growing interest in contributing to the model development, and be in a position to use the increasing amount of supercomputing resources that were being made available through NCAR and DOE. For that last objective, there was considerable effort on the software development front to make the components of CCSM2 more suited to distributed supercomputing environments. There are also a number of major scientific differences between CSM1 and CCSM2. The resolution of the ocean model was increased (3° x 3° vs. 1° x 1°) and the physics of the ice model revamped to include more ice thickness categories and a modified rheology. The land model was completely revised both in its physical formulation and in anticipation of moving toward biogeochemical processes. The atmospheric model was modified to incorporate additional vertical resolution, a prognostic formulation for cloud water, significant improvements to the treatment of clouds and radiation, and a modified treatment of moist convection, along with a variety of other less visible changes that made for a more flexible and accurate modeling infrastructure.

a. The 1000-Year CCSM2 Control Simulation

In the fall of 2001, a control simulation of CCSM2 began on the IBM computer at the National Energy Research Scientific Computing Center (NERSC). At the outset there was a commitment to carry out a multicentury simulation with this new version of the model. The spin-up procedure of CCSM2 was significantly different than that for CSM1. For the CSM1 model, an uncoupled equilibrium solution of the NCAR CSM Ocean Model (NCOM) was available as a part of the multistage spin-up process. An equilibrium solution of the new uncoupled 1° version of the CCSM2 ocean component was not available due to lack of computational resources. Thus, the spin-up procedure for CCSM2 was initiated with the fully coupled system, where the ocean state began with Levitus climatology. The advantage of this procedure was that the model simulation began from a realistic state. The disadvantage of this procedure was that deep ocean timescales, which are thousands of years, determine the equilibrium timescale for the coupled system. Figure 4 shows the temporal evolution of globally averaged surface temperature in the CCSM2 coupled integration. The

Figure 4. The temporal evolution of globally and annually averaged surface temperature for the 1000-year CCSM2 control simulation. The horizontal reference line is the global mean averaged for years 700–1000.



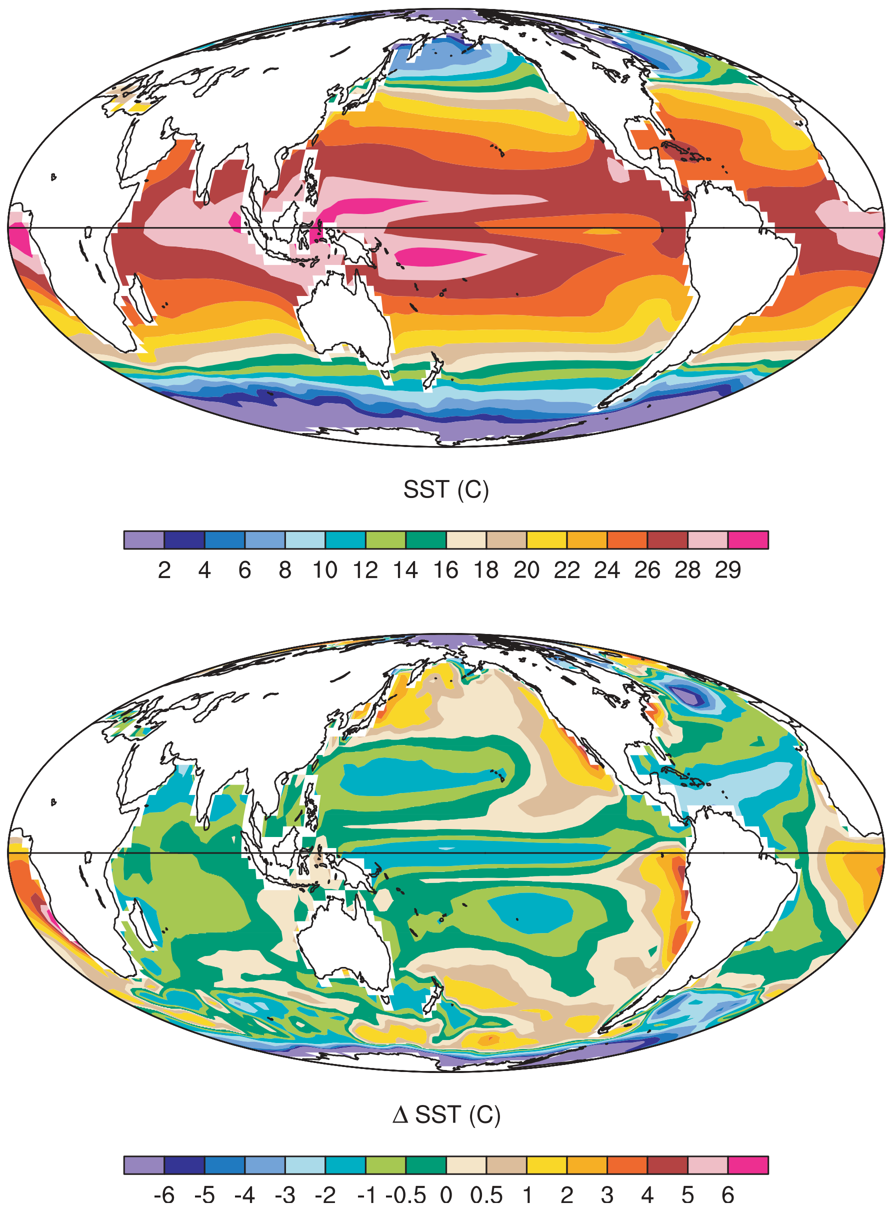
initial 150 years are affected by model drift from the observed sea surface temperatures (SSTs) and sea ice extent into an equilibrium coupled climate.

The control simulation was run for 350 years without flux adjustments. Then three changes were made to the code. The first of the changes was to ensure that all five modules of the CCSM2 use the same set of physical constants. The second change was to correct a “bug” in the ocean component, and the third change was a slight alteration to the ocean equation of state. The last two changes resulted in extremely small changes to ocean-alone solutions. The first change produced a slight, but noticeable, shift in the annual mean state. The simulation was then restarted and run out to year 1000, again with no flux adjustments. Most of this control simulation was run on 144 processors of the IBM SP computer at NERSC. The simulation executed at almost five years per calendar day, and it took seven months to complete 1000 years.

A significant accomplishment of CCSM2 is the greatly reduced drift in deep ocean quantities. Over the first 100 years, the ocean component gained heat, but then it lost heat for the remainder of the simulation. The average rate of ocean heat loss over the last 300 years is 0.25 W/m^2, much smaller than in CSM1. CSM1 contained significant drifts in both deep ocean temperature and salinity. These drifts limited the extent to which the model could be integrated in time. Simulations on the order of 300 years in length were viewed as acceptable for some applications. Thus, CSM1 could be used effectively for century-long climate simulations, e.g., climates of the 20th and 21st centuries. CCSM2 can be integrated for multiple centuries. Indeed, the control simulation performed at NERSC was extended for 1000 years. Given the nominal 1° ocean resolution, this 1000-year simulation established a new international benchmark in climate simulations with fully coupled models.

The biases in SST simulated by CCSM2 are generally considerably less than in CSM1. In particular, the large cold biases over most of the North Pacific and in the Norwegian Sea have been eliminated. On the other hand, some of the biases present in CSM1 remain. The equatorial Pacific Ocean has a cold bias of more than 2°C, and the warm pool in the west is split by colder SSTs on the equator (Figure 5). The simulated SST is too warm in the stratus cloud regions off the western coasts

Figure 5. (top) The mean SST field from years 961 to 980 of the CCSM2 control simulation, and (bottom) the difference between the mean SST of CCSM2 and the Hadley Centre Sea Ice and SST (HadISST) data sets 1982–2001 observed climatology.



of North and South America and Africa, with biases of 5°C in small regions right along the coasts. There is a cold bias of more than 5°C in the SST field in the central North Atlantic Ocean, because the simulated Gulf Stream path is too zonal in this region and does not turn northward around the Grand Banks. The simulation has strong temperature gradients, so that large biases will occur if such features are misplaced. This is a well-known problem with ocean simulations using eddy-permitting but not eddy-resolving resolution. In the Southern Hemisphere, the largest SST errors occur as a result of misplacements of the path of the Antarctic Circumpolar Current (ACC).

Runoff from the Russian rivers is very important to the fresh water balance of the Arctic Ocean. These runoff flows are realistic in the CCSM2 control run. They result in a sea surface salinity field that is quite realistic in the central arctic but a little fresh near the Russian coast. The realistic surface salinity, over much saltier water below 200 m, indicates the presence of a strong halocline in the Arctic Ocean in the CCSM2 simulation. This was not the case in the CSM1, which did not have a true river runoff scheme, and thus did not produce a halocline in the Arctic Ocean.

The simulated areal coverage of sea ice in the Northern Hemisphere (Figure 6) is on the whole much better in CCSM2 than in CSM1, where the sea ice coverage was much too extensive in both the North Pacific and North Atlantic and too thick in the central arctic. The winter extent is somewhat too large, the summer extent is a bit too small, and the average thickness (Figure 7) is too low as compared to observational estimates. In the Southern Hemisphere, as Figure 6 shows, the annual mean extent is too large, especially in the South Atlantic sector. The sea ice thickness distribution around Antarctica is realistic, although the extremes of ice thickness on the east side of the Antarctic Peninsula are too large.

Overall, the CCSM2 atmospheric simulations are considerably more realistic, as compared to observations, than the results from CSM1. The distribution of subtropical stratocumulus clouds is much improved, as is the distribution of precipitable water (Figure 8). Both these quantities are important variables for global change studies. The new model produces less intense precipitation in the eastern equatorial Pacific, which has a positive effect on surface stresses in that region. There remain significant biases in the atmospheric state. The atmosphere overall is too cold, especially the upper tropical troposphere. The distribution and seasonal cycle of tropical precipitation is deficient, with a double Intertropical

Figure 6. Sea ice concentration averaged over the last 20 years of the CCSM2 control simulation in (top) the Northern Hemisphere and in (bottom) the Southern Hemisphere. The thick solid line is the 10% concentration limit from recent observations.

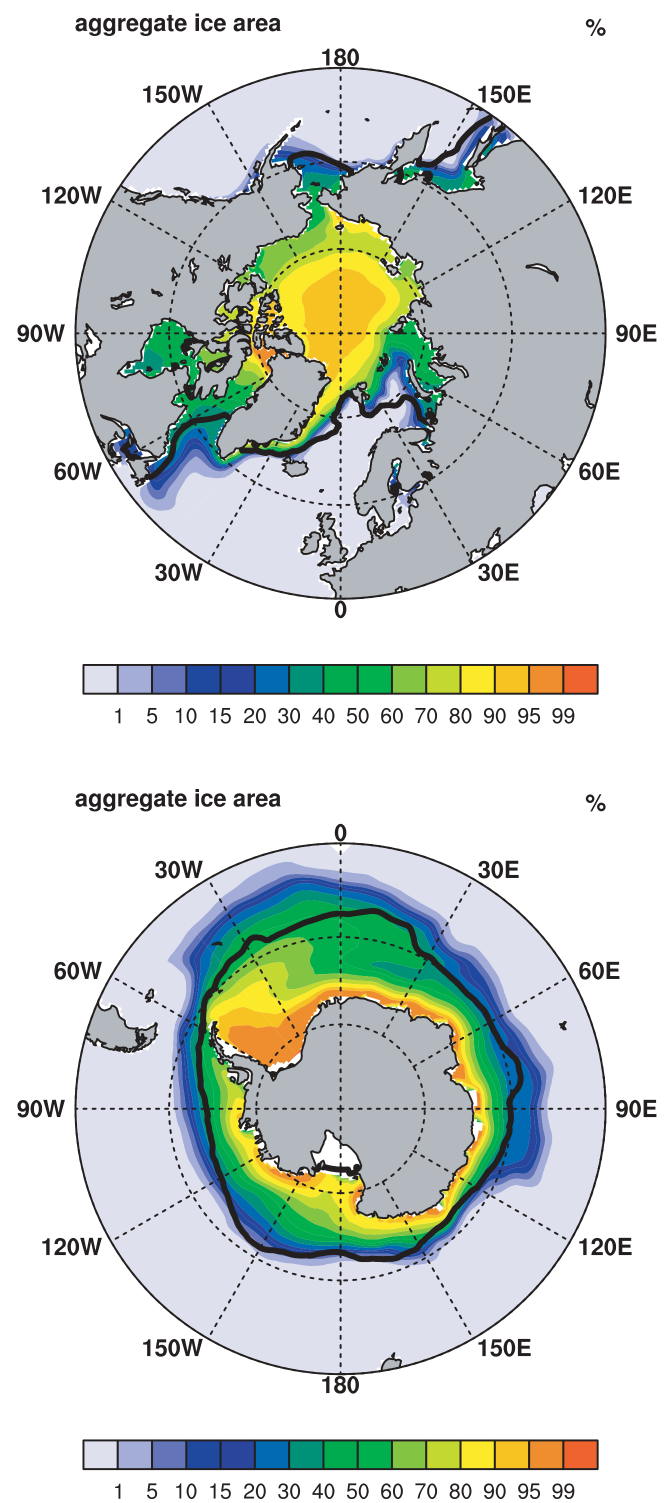
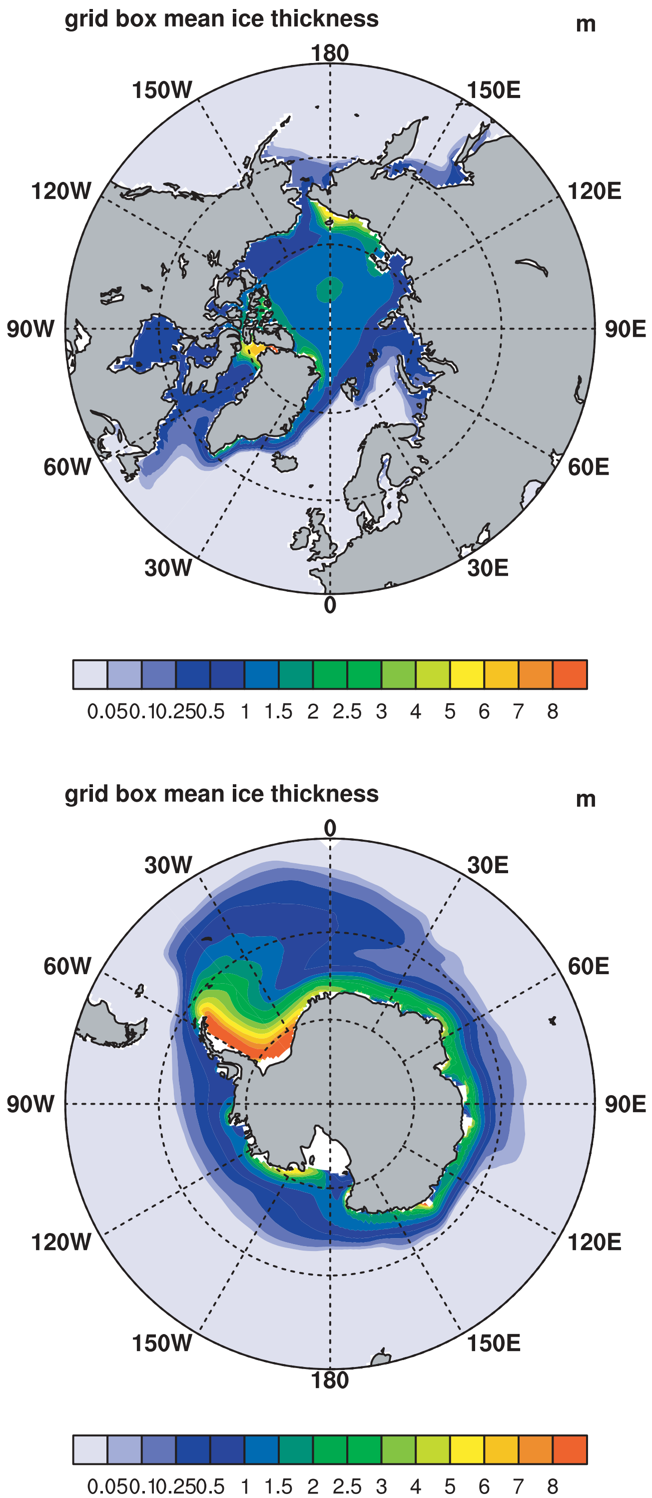


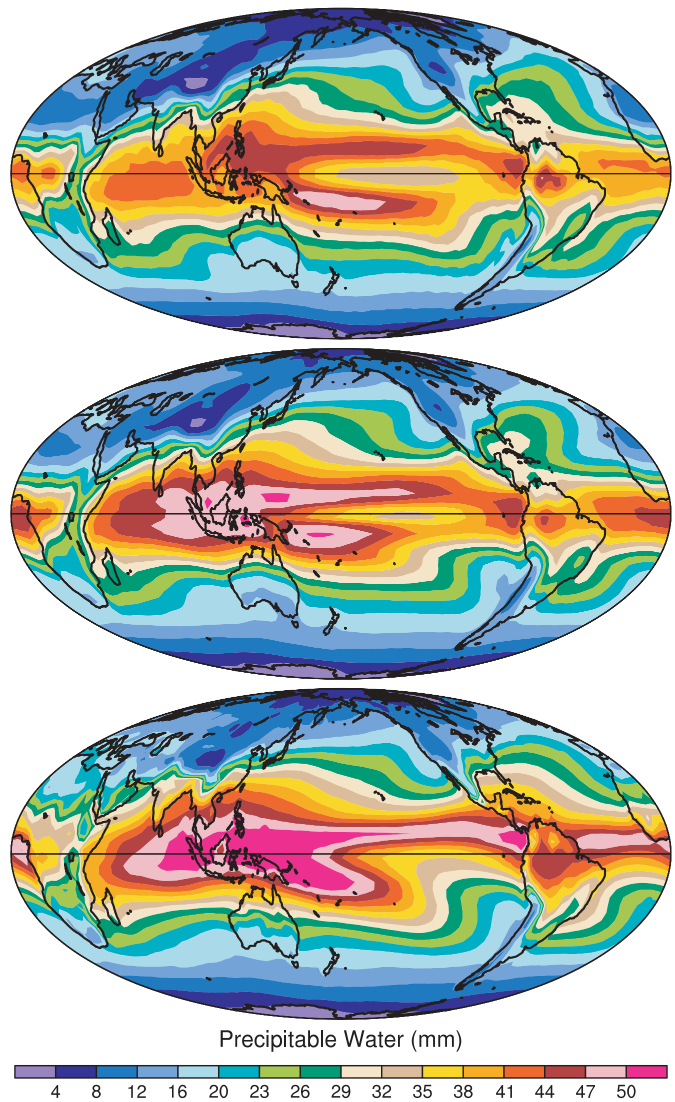
Figure 7. Distribution of simulated ice thickness in the last 20 years of the CCSM2 control simulation, (top) Northern Hemisphere and (bottom) Southern Hemisphere.



Convergence Zone (ITCZ) structure, a feature also exhibited by CSM1 and many other coupled models (Figure 9). Given the biases in the spatial distribution of tropical diabatic heating, the far-field stationary wave response in the extratropics is also biased as it was in CSM1.

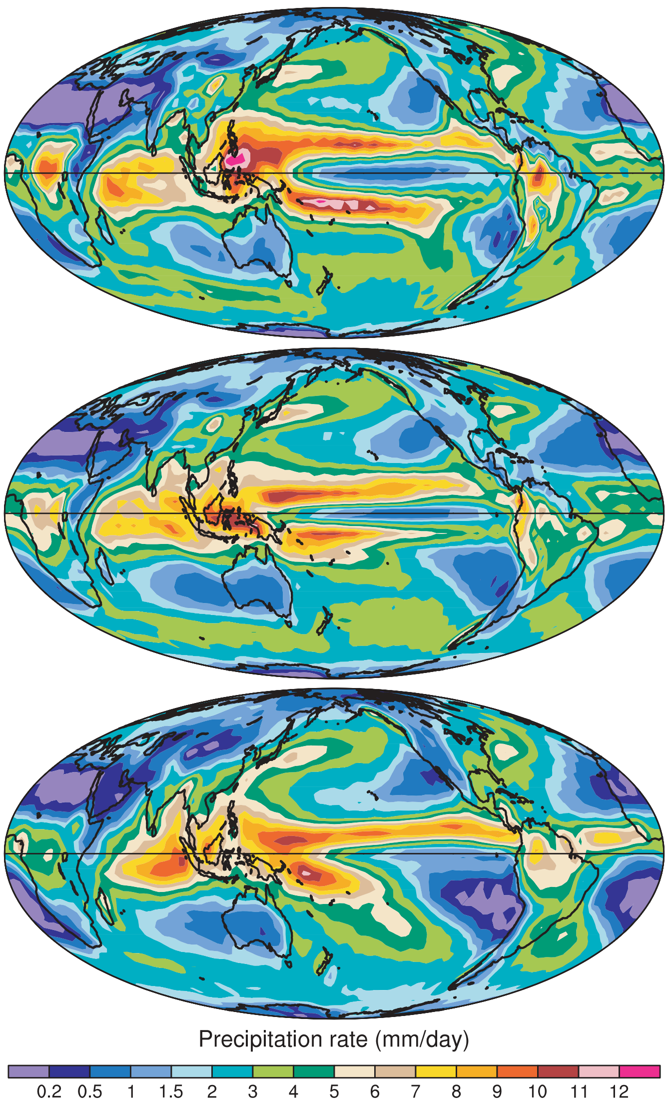
CCSM2 simulations show significant improvements in the surface air temperatures and the hydrological cycle (Bonan et al., 2002a). The new Community Land Model, CLM2, generally warms surface air temperatures in all seasons as compared to the NCAR Land Surface Model

Figure 8. Annually averaged precipitable water for (top) the last 20 years of the CSM1 control run, for (middle) the last 20 years of CCSM2 control run, and for (bottom) the NASA Water Vapor Project (NVAP) 1988–1997 climatology.



(LSM), reducing or eliminating many cold biases prominent in CSM1. The simulated annual precipitation over land is reduced somewhat, bringing the model closer to observation estimates. Changes in the cold region hydrology greatly improve the annual cycle of runoff in the arctic and boreal regions, where the model has low runoff in the cold seasons and high runoff during the snow melt season. This has a major positive impact on the simulation of the properties of the Arctic Ocean.

Figure 9. Annually averaged precipitation rate for (top) the last 20 years of the CSM1 control run, for (middle) the last 20 years of CCSM2 control run, and for (bottom) the Climate Prediction Center Merged Analysis of Precipitation (CMAP) 1979–1998 climatology.



The variability exhibited by CCSM2 is much improved over that of CSM1 both in the tropical regions and high latitudes, although a later release of CSM1 showed improved tropical variability (Otto-Bliesner and Brady, 2001). The time series of monthly anomalies of SST in the Niño3 region (Figure 10) shows that the El Niño–Southern Oscillation (ENSO)–type fluctuations in CCSM2 have a much larger amplitude than those in CSM1. A spectral analysis of that time series (Figure 11) shows that the amplitude of the oscillations simulated by CCSM2 compares quite well to observational estimates. On the other hand, the frequency distribution of CCSM2 is narrow and the peak frequency is at 2 to 3 years, rather than the observed broad peak of 3 to 7 years. The ENSO variability is too strong farther to the west along the Pacific equator, where the amplitude is comparable to that in the Niño3 area. This is a direct consequence of the cold tongue of SST being too strong and extending too far west, generating too much variability when equatorial ocean upwelling switches on and off.

Figure 10. Monthly Niño3 SST anomalies for 100 years for (top) CSM1 and (bottom) CCSM2.

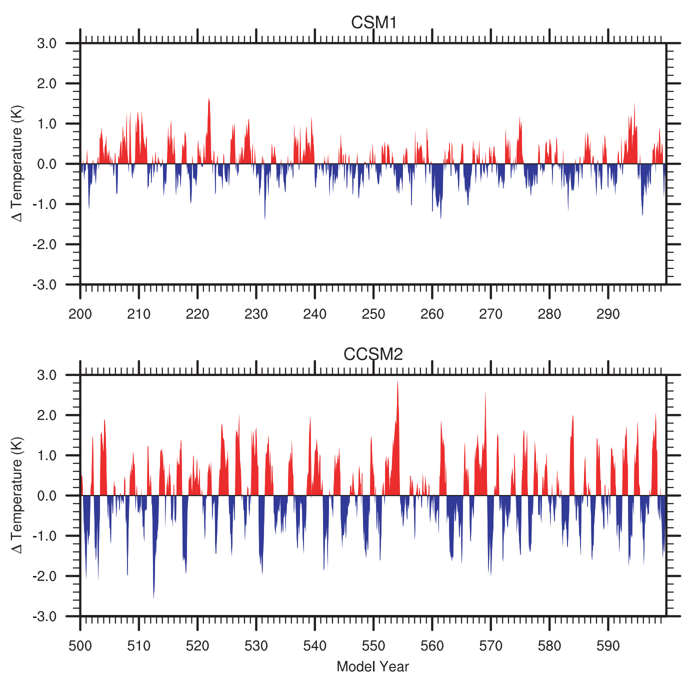
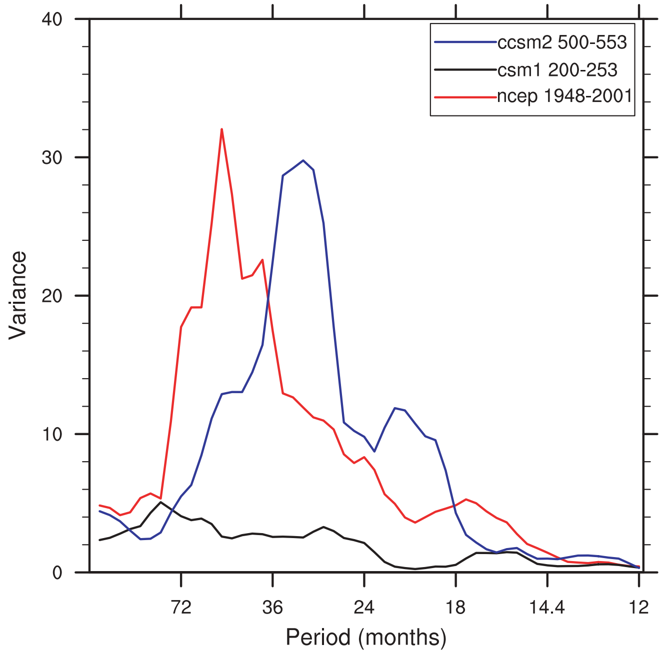
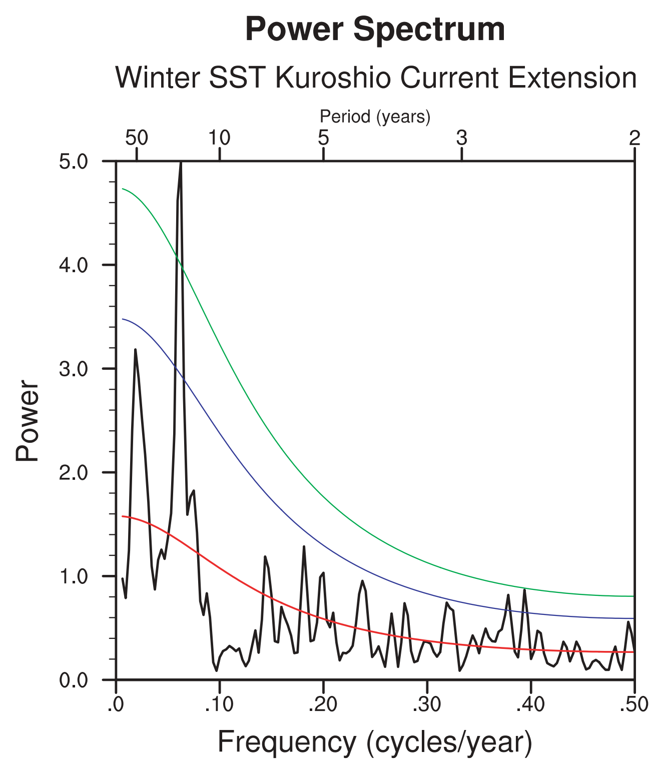


Figure 11. Power spectra of 54 years of monthly Niño3 SST anomalies from CSM1 control run, from CCSM2 control run, and from the National Centers for Environmental Prediction (NCEP) re-analyses.



An example of decadal variability in the CCSM2 control run is illustrated in Figure 12. This figure shows wintertime SSTs (departures from normal) in the region of the Kuroshio Current Extension over the North Pacific. Fluctuations with a quasi-decadal periodicity are apparent. The power spectrum of this time series reveals a spectral peak around 16 years that exceeds the null hypothesis of a first-order Markov process. The 16-year variability likely originates from oceanic processes, as the net air-sea heat flux acts to damp the SST anomalies. Subsurface thermal anomalies are consistent with the idea that the decadal periodicity in SST reflects natural variability of the ocean gyre circulation. Further analysis is under way to understand the mechanisms responsible for the 16-year spectral peak in SST along the Kuroshio Current Extension.

The CCSM2 realistically captures the spatial pattern of the North Atlantic Oscillation (NAO), but the amplitude is slightly weaker than in recent observations. This amplitude discrepancy could be because of the difference between a control run with fixed external forcings, such as the solar



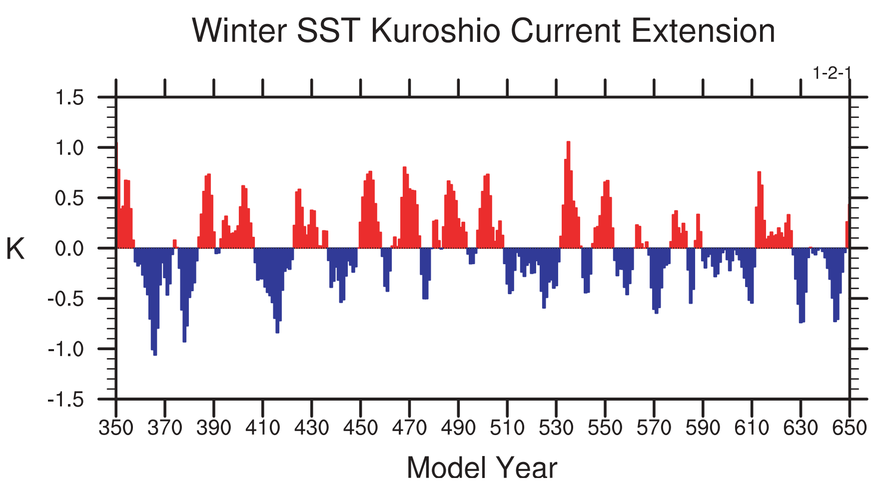


Figure 12. (left) Time series of wintertime SST departures from average in the Kuroshio Current Extension and (above) power spectrum of the time series at left showing significant spectral peak at 16 years.

constant and the carbon dioxide concentration, and the real world, where the climate forcings are changing (Gillett et al., 2003). In addition, Holland (2003) documents that the variability in the arctic sea ice and the surrounding ocean forced by wind changes associated with the NAO are also realistic in the control simulation. A high NAO index has stronger westerlies across the North Atlantic, forcing stronger transport of warm Atlantic water into the Greenland/Iceland/Norwegian and Barents Seas. This, in turn, reduces the sea ice cover in these seas, but results in more extensive sea ice cover in the Labrador Sea. This can change the location of the deep water formation that drives the thermohaline circulation in the North Atlantic.

b. The Climate Sensitivity Simulation

The climate sensitivity of coupled models is defined as the ratio of the equilibrium change in global mean surface temperature to the initial forcing of the climate system. This definition strictly requires models to be run to equilibrium, which for a fully coupled, full depth ocean model at the resolution used by CCSM2 is computationally very expensive. Thus, to obtain an estimate of climate sensitivity, the fully dynamic ocean models are replaced with slab ocean models that employ prescribed ocean heat transports. The Community Atmosphere Model (CAM2) has been coupled to a slab ocean model and the same thermodynamic sea ice model used in CCSM2. This model has been forced with an instantaneous doubling of atmospheric carbon dioxide, which produces an initial forcing of 4 W/m^2 at the tropopause. Figure 13 shows the temporal evolution of the global mean surface temperature due to a doubling of CO_2. Equilibrium is reached in approximately 30 years, with a change in surface temperature of about 2 K. Thus the predicted model sensitivity is 0.5 K/W/m^2. This is the same climate sensitivity exhibited by CSM1. This sensitivity is roughly a factor of two smaller than a number of other coupled system models, such as the National Oceanic and Atmospheric Administration's (NOAA) Geophysical Fluid Dynamics Laboratory (GFDL) model and the United Kingdom Meteorological Office (UKMO) Hadley Centre model.

Another means of estimating climate sensitivity in the fully coupled version of CCSM2 is to perform a transient simulation where atmospheric CO_2 increases at a rate of 1% per year from some point in the control simulation. The advantage of this type of simulation is that the full model is used to estimate sensitivity and that the transient forcing can easily be applied across many models, thus facilitating comparison of transient climate response. Figure 14 shows the transient change in global mean surface temperature for CCSM2 due to a 1% per year increase in CO_2. Given this rate of increase, atmospheric CO_2 doubles near year 70 of the simulation and quadruples at year 140. The linearity of the curve is due to the fact that the response is proportional to

Figure 13. Time series of the global mean surface temperature after an instantaneous doubling of CO_2, using CAM2 and the slab ocean model. The blue line is the control run.

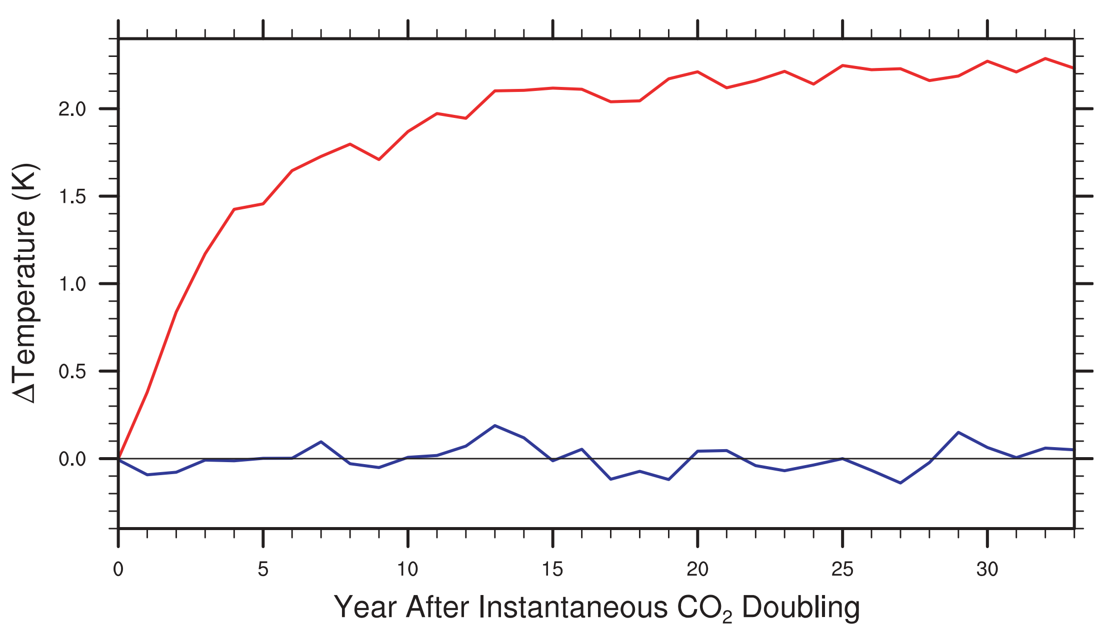
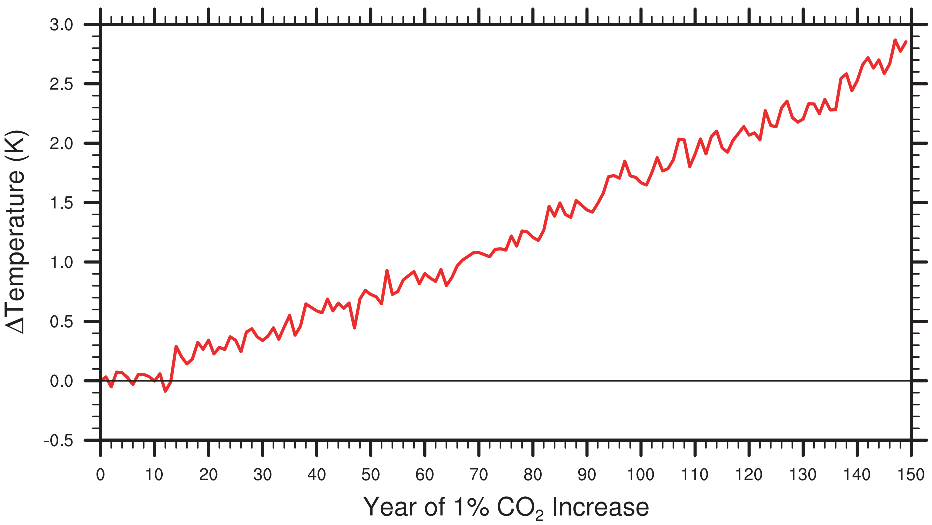


Figure 14. Time series of global annual surface temperature as simulated by CCSM2 when forced by a 1% per year increase in CO_2. Doubling of CO_2 occurs at year 70.

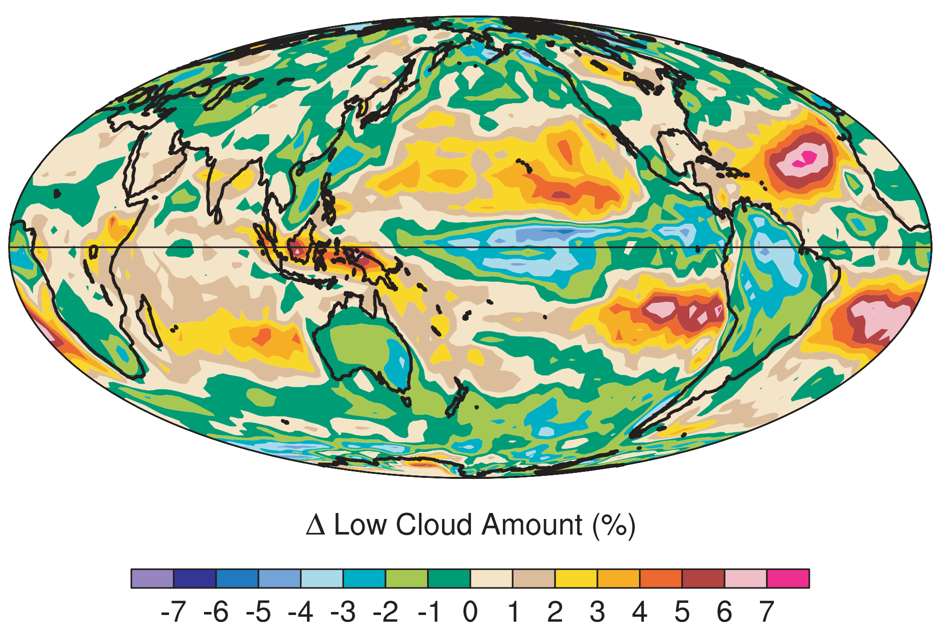


forcing, while the forcing is proportional to the logarithm of the CO_2 concentration. The projected change in global mean temperature at the time of doubling is 1 K, which is, again, lower than in most other models.

A major determinant of climate sensitivity is cloud feedback. An increase in low cloud with increased surface temperature leads to a reduction in short-wave energy absorbed at the surface and thus acts to dampen surface warming, i.e., a negative feedback. Figure 15 shows the change in low cloud from the equilibrium slab ocean simulation. There are low cloud increases over large regions of the oceans, which is an effective negative feedback on the climate system, and may be connected with the low climate sensitivity. A focused climate sensitivity analysis is part of the research agenda of the CCSM program. The accuracy of the CCSM cloud prediction scheme will be tested against observations for different regions and temporal scales. For example, in the tropics there are observed large-scale changes in cloud cover related to the ENSO phenomenon. These changes occur in the western and eastern equatorial Pacific regions and involve low, middle, and high clouds. Thus, a necessary test of any climate cloud prediction scheme is to accurately reproduce the observed changes in clouds due to this natural mode of variability. Similar tests can be applied to the models for extratropical clouds and decadal scale modes of variability, i.e., the NAO and Pacific Decadal Oscillation (PDO).

This analysis is necessary but not sufficient to determine if model-simulated cloud changes due to global warming are realistic. Models will need to be compared to observed long-term trends in cloud cover as well. In addition to this comparison, CCSM2 will be compared to other climate system models to determine the reasons for intermodel differences in climate response to increased greenhouse gases. The near-term focus of this activity is collaboration with NOAA's GFDL.

Figure 15. The change in low cloud amount for a double CO_2 simulation using CAM2 and the slab ocean model.



c. The Experience of Community Model Development

The CCSM effort is unprecedented in the climate modeling community. The original goal of the program was to develop a climate system model through the collaboration of scientists within and outside NCAR. The complexity of this effort has exceeded original expectations. As described in the history, the original development took place mainly within NCAR, but the commitment to expand this process to a true community effort was always a part of the CCSM plan. In the expansion of this process, a number of lessons were learned concerning building and maintaining a large-scale community modeling effort. It is timely to summarize our experiences to help members of the community understand the important issues involved in managing the CCSM program. Hopefully these "lessons learned" will aid the future development of the CCSM program.

The challenges of building a community model are manifold. Given that creative ideas originate from creative individuals, that scientists tend to be individualistic with their unique approaches to problem solving, and that scientists seek rewards for their creativity, it is a challenge to create a community effort that motivates scientists to work on a common goal.

Such an effort must begin with a set of commonly agreed-upon goals. For the CCSM effort, this was always envisioned as creating a fully coupled model of Earth's climate system, a model that would not rely on artificial flux adjustments and whose source code and output would be freely and openly available to the greater community. Accomplishing these general goals involves a number of important questions. How comprehensive should the climate system model be? Should it include only basic physical processes? If it includes chemical and/or biological processes, how extensive and complex should these processes be? What are the envisioned applications of the climate system model? Will the complexity of the model actually limit its applicability to certain scientific problems? How should the model code be structured? What architectures should the model run on? These are just a few of the issues that need to be agreed upon to create a community model.

A major challenge is how to build a model that best serves the needs of a diverse community. It is becoming increasingly demanding to have a single model that serves all users. For example, the paleoclimate community cannot use a model that requires complex boundary data for various ecological or biogeophysical processes that are unavailable for times in the historical or geologic past. The CCSM process has attempted to address issues of this sort through diverse representation on the SSC and with input from the working groups. The science plan is one way to articulate what should and should not be a part of the CCSM effort. The extent to which the community participates in the development of this plan will influence the structure of the model.

Organization of the CCSM depends on a workable governance structure, an optimal management structure, and effective communication. The governance of the scientific direction of the CCSM activities occurs through the SSC. Half of the SSC members are from NCAR, while the other half are from institutions outside NCAR. Although this balance is important to include a diversity of views, it remains a challenge to maintain close communication among the SSC members. The SSC meets three times a year, with some members also attending the CAB meeting in Washington, D.C., in January. These meetings enable the SSC to discuss the direction of the CCSM process, organize the annual workshop, and receive updates from working groups. However, the actual development of the model occurs on a much shorter timescale. Thus, the chairman of the SSC and a few scientists must make many of the decisions on the detail of the evolution of the model at NCAR.

Another challenge to the organization of CCSM is effective communication between the SSC and the working groups and across various working groups. The SSC meets with the working group co-chairs at the annual workshop. This gives the working groups an opportunity to voice their concerns and needs to the SSC. The CCSM coordinator attends all of the working group meetings and meets individually with each of the working group co-chairs to facilitate communication between the working groups. Some key questions in the governance of the CCSM focus are:

- How centralized does the management need to be?
- How does the SSC ensure inclusiveness in the process?
- How does the SSC motivate a community of volunteers?

Considerable centralization of the model development has been found to be essential. There must be an institutional home for the modeling activity, given the magnitude of the software engineering. However, the scientific development of the CCSM needs to be distributed across the nation. The working group structure is the SSC's best attempt to address the balance between centralized and distributed processes and to be inclusive. Of course, with inclusiveness comes the possibility (almost assurance) that competing proposed changes and/or additions to the model will exist. Thus, a decision process is needed to select the most appropriate aspects of the model. The working groups have created a variety of methods by which such decisions are made, as illustrated in working group minutes and procedure on the respective websites.

Traditionally, the means of motivation for working group members is access to model output, computational resources, and limited software engineering support. Although these are important means to motivate individuals, the implication is that the CCSM is mainly a voluntary effort. The lack of a well-defined reward structure remains a challenge to CCSM, and discussion with funding agencies may be required to find a solution to the problem. Key also to keeping members involved is a sense of ownership. It has proven a challenge to grow this sense of ownership. Communication involves exchange of information within the CCSM effort, but also dispersal of information about CCSM out to the greater community. The annual meetings were designed to enhance communication mainly within the CCSM community, and they have been quite successful. A brochure on the CCSM was produced to enhance contact with the broader community. However, the most effective means to increase awareness of the CCSM is to communicate scientific results in the peer-reviewed literature. To achieve this, the CCSM effort needs to move beyond model development and software design to address more scientific questions.

The software development of the CCSM requires a high level of coordination among all those involved in the process. The lessons learned on this activity have been substantial. The development of the model code involves software engineers not only at NCAR, but also at a number of centers around the United States. A code repository system is used to maintain the code and its variants. Additions to this repository occur almost daily. To prevent conflicting additions to the repository, a Change Review Board (CRB) structure was instituted in the fall of 2002. The boards meet frequently at NCAR to review proposed changes to the code. The main purpose of the boards is to evaluate the documentation of the proposed changes, the implications for model performance, and potential conflicts. As the CCSM effort grows, even more expanded infrastructure will be required to manage this large modeling effort.

Growth in the CCSM effort has placed severe demands on both human and computational resources. Evolution of the CCSM to a more comprehensive systems model will require more scientist involvement, more support for these scientists, and more software engineering support. The *CCSM Strategic Business Plan* describes some of the key personnel needed for the effort. A more immediate concern is that the scientific support for core atmosphere and ocean model development at NCAR is eroding, and the remaining staff are aging. This basic model development capability must be maintained over the long term if NCAR is to fulfill its role in CCSM.

Management of existing computational resources has been a challenge to the CCSM program. The CCSM has a substantial computational allocation from the Climate Simulation Laboratory, access to NSF supercomputer facilities, access to a number of DOE supercomputers, and potential access to the Earth Simulator in Japan. Porting the CCSM to all of these architectures places a great demand on the CCSM Software Engineering Group (CSEG) at NCAR. Even after porting the model, a person is required to constantly ensure the model is running and that model output is archived in an optimal manner. Ensuring that all the resources are used efficiently and completely has proven to be a considerable challenge, especially given the limited human resources available to attend to all of the systems. A more effective means of optimally managing computational resources is required for CCSM.

The rewards of community modeling are the ability to address big science questions that require a complex system model and the experience of working as a community on a project greater than the sum of its parts. However, the development, management, and coordination issues have become a full-time and exceptionally demanding job for some of the NCAR scientists and support staff who are central to the CCSM project. It is vital to the success of the project that its core staff not be overcommitted and be in a position to enjoy the activity and the science that results.

IV. The Status of the Community Climate System Model

This section provides a snapshot of the state of the model components of the CCSM, as well as some indication of the anticipated direction of the development of these components. Such documentation is transitory at best; model development is really a continuous process as model simulations are continually confronted with existing data, new data, and new analyses. Nevertheless, this section is intended to give a sense of where the model is and, in general, where it is likely to go in the short term. In a later section, new or more extensive scientific questions and issues are raised that will likely require a major model development effort.

a. The Atmosphere Component

A new version of the atmosphere component of CCSM2, CAM2, was released to the community in June 2002. There are a number of significant improvements and enhancements in the physical parameterizations, dynamical treatments, and software engineering of the model. The improvements to the physics include:

- a detailed thermodynamic sea ice model (Bitz and Lipscomb, 1999)
- updated prognostic cloud water (Rasch and Kristjansson, 1998) (Zhang et al., 2003)
- generalized cloud overlap in radiation (Collins, 2001)
- more accurate formulation of water-vapor radiative effects (Collins et al., 2002)
- fractional ice and land consistent with CCSM2
- enhancement of evaporation of convective precipitation

The improvements to the dynamics include:

- addition of an optional finite volume dynamical core developed through collaboration with the National Aeronautics and Space Administration (NASA)
- new options for coupling the physics and dynamics

The data sets used to force the atmosphere model include a new, state-of-the-art SST and sea ice time series since 1949 (Hurrell et al., 2003). The Climate Variability Working Group (CVWG) has used this data set to create a large ensemble of CAM2 integrations for the last 50 years. These integrations can be used to study various oscillations of the climate system (e.g., the NAO) and to quantify the fidelity of the simulated climate. The ensemble data sets are available via the CVWG website.

The CAM2 source code, documentation, initial and boundary data sets, and control integrations complete with diagnostic analysis have been released to the climate community via the Web. The code has been tested on six different computer architectures that are popular for climate research applications.

The major improvements in the atmosphere component of the climate simulated by CAM2 relative to the previous Community Climate Model, CCM3, include:

- much more realistic distributions of precipitable water in the tropics
- much more realistic clear-sky long-wave fluxes in polar regions
- better representation of cloud response to SST variations during ENSO

A major activity of the Atmosphere Model Working Group (AMWG) has been the identification and diagnosis of the systematic errors in the climate simulated by CAM2. The biases include a double ITCZ, underestimation of tropical variability, overestimation of land surface temperatures in winter, underestimation of tropical tropopause temperatures, and systematic biases in the boundary layer clouds and surface fields in the Eastern Pacific. The AMWG has decided that the highest priority is to analyze and address these errors in collaboration with other working groups, so they have begun a systematic set of experiments to explore methods for ameliorating or eliminating these biases.

Diagnosis of the simulated climate has been facilitated by a comprehensive suite of model diagnostics. These diagnostics include comparisons against a variety of observational data sets and several global meteorological analyses. The diagnostic package was developed in parallel with CAM2, and the code and data sets for the package are readily available via the Web. The diagnostics are undergoing continuous enhancement to enable the CAM2 community to document and improve the model. Recent extensions include the complete set of the Working Group on Numerical Experimentation (WGNE) diagnostics of variability over a wide range of spatial and temporal scales.

In parallel with these efforts, the physics and dynamics and its numerical representation continue to undergo rapid development in collaboration with partners in universities and national laboratories. The AMWG continues to play a central role as a venue for users and developers of CAM2 to meet and discuss ongoing research. In preparation for the integrations for the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report, the AMWG is investigating a number of significant potential improvements to CAM. These will be implemented in an official release of CCSM ready in late 2003. The improvements include:

- explicit prognostic treatment of cloud phase in addition to cloud water
- improved energy conservation by the physics and dynamics in the atmosphere
- a realistic three-dimensional time-varying specification of major aerosol species for calculation of aerosol radiative forcing on the climate system
- a more accurate and updated parameterization for the absorption of solar radiation by atmospheric water vapor
- an updated parameterization for the absorption of infrared radiation by water vapor

b. The Land Surface Component

The land surface component of CCSM2 is the CLM2 (Bonan et al., 2002a). This is a completely revised land surface parameterization as compared to the NCAR LSM (Bonan, 1996, 1998). Much of the biogeophysics and hydrology is based on Zeng et al.'s (2002) Common Land Model, which combines many of the features of the biosphere-atmosphere transfer scheme (BATS, Dickinson et al., 1993), the NCAR LSM (Bonan, 1996), and the IAP94 (Dai and Zeng, 1997) land models. The CLM2 significantly reduces the cold summer surface air temperature bias found in CCM3 and CSM1 by reducing latent heat flux and increasing sensible heat flux, and it improves the annual cycle of runoff and better simulates snow mass (Zeng et al., 2002). Table 1 shows the major parameterization differences between CLM2 and the NCAR LSM.

Table 1. Comparisons of some basic characteristics of CLM2 and LSM.

CLM2	LSM
10 layers for soil temperature and soil water with explicit treatment of liquid water and ice	6 layers
Up to 5 layers of snowpack depending on snow depth	One snow layer blended into the first soil layer
Runoff parameterization to simulate runoff from saturated and unsaturated zones that uses concepts from the TOPMODEL hydrology model	Runoff parameterization that distinguished these 2 zones using an exponential distribution of soil water

CLM2 explicitly resolves surface heterogeneity data (Bonan et al., 2002b). Each model grid cell is divided into four primary land cover types: glacier, lake, wetland, and vegetation. The vegetated portion of a grid cell is further divided into patches of up to 4 of 16 plant functional types (PFTs), each with its own leaf and stem area index and canopy height. Bare ground is represented not as a primary land cover type, but rather as an unvegetated patch occurring among the PFTs. The relative area of each subgrid unit, the PFT, and the leaf area index are obtained from 1 km satellite data. Not all grid cells contain four PFTs. Homogenous vegetation may have fewer PFTs than mixed vegetation. The soil texture data set allows vertical profiles of sand and clay.

Simulations with CLM2 coupled to CCM3 show significant improvements in surface air temperature, snow cover, and runoff compared to NCAR LSM (Bonan et al., 2002a). CLM2 generally warms surface air temperature in all seasons compared to NCAR LSM, reducing or eliminating many cold biases. Annual precipitation over land is reduced from 2.35 mm/day in LSM to 2.14 mm/day in CLM2. The hydrologic cycle is also different. Transpiration and ground evaporation are reduced. Leaves and stems evaporate more intercepted water annually in CLM2 than LSM. Global runoff from land increases from 0.75 mm/day in LSM to 0.84 mm/day in CLM2. The annual cycle of runoff is greatly improved in CLM2, especially in arctic and boreal regions where the model has low runoff in cold seasons when the soil is frozen and high runoff during the snow melt season.

Most of the differences between CLM2 and LSM are attributed to particular parameterizations rather than to different surface data sets. Important processes include multilayer snow, frozen water, leaf interception of precipitation, soil water limitation to latent heat, and higher aerodynamic resistances to heat exchange from ground. Control simulations with CAM2 and CCSM2 show that surface air temperature is well simulated except, most noticeably, in high latitudes of the Northern Hemisphere, which have a large (several degrees) warm bias in winter. Changes to fractional snow cover seem to be a promising way to reduce warm winter temperatures in the Northern Hemisphere. Daytime ground temperatures can be excessively high due to low within-canopy aerodynamic conductance. Improvements to the fractional snow cover and within-canopy turbulent exchange will be implemented when testing is finalized.

Other near-term changes to the model include a new 2 m temperature parameterization using a grass tile that is included in each grid cell, and new leaf temperature equations that are numerically more efficient. Evaporation of intercepted water can also be excessively high. Active research is ongoing to understand and reduce this bias.

Inclusion of the carbon and nitrogen cycles, biogeochemistry, and dynamic vegetation is a high priority for the development of the land model. Several structural and functional modifications are being made to facilitate this work. The primary structural change consists of replacing the single vector of subgrid land cover patches extant in CLM2 with a nested hierarchy of subgrid types. The new hierarchy includes the following nested grid and subgrid types: Gridcell; Landunit, representing geomorphologically distinct subgrid regions within a grid cell (e.g., glacier, lake, wetland, vegetated); Column, whereby each landunit consists of one or more snow and soil columns; and PFT, in which each column consists of one or more PFTs (e.g., grass, broadleaf deciduous tree, needleleaf evergreen tree). This nested hierarchy allows for greater representation of subgrid surface heterogeneity. For example, the vegetated land unit in a grid cell may consist of several soil columns representing different soil textures. Several PFTs may occur individually or together on each soil column.

The CCSM Land Model Working Group (LMWG) and the CCSM Biogeochemistry Working Group (BGCWG) have endorsed this code. Within this model structure, active research is under way to implement carbon and nitrogen cycling. The primary goal of this research is to provide an accurate net flux of CO_2 between the land and the atmosphere. The strategy being pursued to accomplish this goal is to use the best available observations to evaluate uncoupled simulations across the widest possible range of spatial and temporal scales, make modifications to the biogeochemistry algorithms as dictated by these evaluations, and incorporate these algorithms into the coupled model. Additional biogeochemical work, in collaboration with the BGCWG, is under way to include emissions of biogenic volatile organic compounds, dust emission, dry deposition, and isotopes of water and carbon.

Another major research focus is to study the impact of natural and human changes in land cover and land use on climate. Land uses include conversion of natural vegetation to cropland, soil degradation, and urbanization. The data sets and new parameterizations needed to quantify these impacts on climate are being developed in collaboration with the Climate Change Working Group (CCWG). The climate feedbacks associated with natural changes in land cover are being assessed by developing and implementing a model of natural vegetation dynamics for use with CLM.

c. The Ocean Component

The ocean component of the CCSM2 uses the Parallel Ocean Program (POP) code, developed at Los Alamos National Laboratory (LANL) (Smith et al., 1992). The ocean grid uses spherical coordinates in the Southern Hemisphere, but in the Northern Hemisphere, it uses an orthogonal curvilinear grid in which the pole has been displaced to 77°N, 40°W (inside Greenland), and which matches smoothly onto the southern spherical grid at the equator. Displacing the pole inside a land mass removes the grid singularity that requires very small time steps, and it is no longer necessary to add an artificial one-cell island at the North Pole, as was done in CSM1. The horizontal grid has 320 x 384 grid points and there is enhanced meridional resolution near the equator. This is twice the horizontal resolution of the CSM1, allowing better representation of western boundary currents, such as the Gulf Stream, and narrow straits. For example, the Bering Strait is open in the CCSM2, but not in CSM1. There are 40 levels in the vertical, about the same as CSM1. The horizontal viscosity is represented by a Laplacian operator that is anisotropic. Both coefficients are spatially variable, based on the scheme described in Smith and McWilliams (2002). The time step used is one hour, and no Fourier filtering is required in the Arctic Ocean. In CSM1 strong Fourier filtering was required in the arctic because of small cell widths near the grid singularity at the North Pole.

The parameterization of the effects of mesoscale eddies is that of Gent and McWilliams (1990), which was also used in CSM1. However, it is now implemented as a skew-diffusion term, as described in Griffies (1998), using a new and very accurate numerical algorithm. The vertical mixing scheme is the K-profile parameterization (KPP) scheme of Large et al. (1994), which was also used in the CSM1.

The CCSM2 ocean component uses a new, and much more accurate, equation of state for sea water from McDougall et al. (2002). There is now a real river runoff scheme, unlike CSM1. The land model calculates and routes runoff, which can go either directly into the active ocean domain or into a marginal sea. The water budget in these marginal seas is balanced, and the excess or deficit of water is included in the adjacent active ocean as an implied salt flux.

The higher ocean horizontal resolution gives faster and narrower western boundary currents and equatorial currents than CSM1. The equatorial currents were improved by including an anisotropic horizontal viscosity in CSM1.4, but the CCSM2 equatorial currents are better still. The transport through Drake Passage is very much better than in CSM1.

The simulated Gulf Stream does not go north around the Grand Banks but heads northeast across the Atlantic toward Europe, just as in CSM1. This leads to large errors in SST and sea surface salinity in the central North Atlantic. The higher ocean resolution has not helped to get the correct North Atlantic Current path, but it does allow sharper gradients across the Gulf Stream. This leads to larger local errors than in the lower-horizontal-resolution ocean component of the CSM1.

Displacing the North Pole in the CCSM2, eliminating Fourier filtering, opening the Bering Strait, and having a realistic river runoff scheme have led to a very much improved simulation of the Arctic Ocean compared to that of CSM1. CCSM2 has a realistic halocline in the Arctic Ocean and flow through the Bering Strait, whereas CSM1 had neither. This has helped CCSM2 to simulate the mean arctic sea ice distribution and its interannual variability very realistically.

The ocean component can easily be configured to do ocean-alone runs. It can be run with the coupler and “dummy” atmosphere, land, and sea ice components. The latter three provide the atmospheric forcing, river runoff, and sea ice distributions, respectively, needed as boundary conditions for the ocean. Runs have been made where the atmosphere forcing comes from observations, such as the National Centers for Environmental Prediction (NCEP) re-analyzed fields from 1958 to 2000, and using five years of daily data generated by a stand-alone run of the CCSM2 atmosphere and land components. These ocean simulations then can be compared to that obtained in the fully coupled CCSM2 control run.

The CCSM Ocean Model Working Group (OMWG) has identified a number of algorithmic developments and testing that need to be conducted for the CCSM2 ocean component. The POP ocean component uses a solar penetration parameterization that is globally uniform and assumes that the water is Jerlov type Ib (Paulson and Simpson, 1977). In reality, the solar penetration varies with location and season. An improved parameterization, which includes spatial and temporal variations, is needed that should be based on satellite observations of chlorophyll. Recent oceanographic observations strongly suggest that vertical mixing in the deep ocean is enhanced over regions of rough topography and is at a minimum over the very smooth abyssal plains. A parameterization to mimic this process could be useful. Eddy energy is very spatially inhomogeneous in the ocean, so that the parameter in the Gent-McWilliams eddy parameterization scheme should be spatially dependent. The Visbeck et al. (1997) scheme and an anisotropic version of the Gent-McWilliams scheme are both implemented in POP, but the response of the ocean simulations to this modification should be explored before either can become the standard parameterization.

The partial bottom cells that have been incorporated into the model enable a much smoother and more realistic representation of the ocean topography. This should lead to a less noisy solution and to more realistic deep ocean currents. The Beckmann and Doscher (1997) bottom boundary layer scheme has been tested, but it only slightly improves the model solutions in the deep North Atlantic. Nevertheless, at least the diffusive part of this scheme will be included in the CCSM2 ocean component in the near future.

The present third-order upwind advection scheme succeeds in suppressing values of the potential temperature and salinity that are outside oceanographic ranges. However, out-of-range tracer values are much more of a problem when transporting biogeochemical tracers. This problem requires exploration of more refined, and expensive, advection schemes that preserve tracers between specified lower and upper limits.

The present ocean component has a fixed volume of water, and the exchange of fresh water across the upper boundary is converted into an equivalent salt flux. In the real ocean, fresh water mass is exchanged, modifying the volume of the ocean. This natural boundary condition has been implemented in the POP code, and the model runs stably, but more work is needed to implement the fresh water flux boundary conditions under ice. This question needs to be explored before the natural boundary condition can become the standard way to run the ocean component.

New grid-generation software has been developed that permits much more flexibility in creating global ocean grids, as well as generating and easily modifying the topography for these grids. This software enables the generation of grids with displaced poles in both Northern and Southern Hemispheres, which will be used by the Paleoclimate Working Group to generate grids corresponding to past orographies where neither geographical pole lies within a large land mass. The new software also allows the generation of so-called "tripole" grids, which can have two poles in the Northern Hemisphere and one pole in the Southern Hemisphere. The advantage of tripole grids is that they have more uniform resolution across the Arctic Ocean. The cell aspect ratios are close to one everywhere.

d. The Sea Ice Component

The CCSM Polar Climate Working Group (PCWG) recommended a number of improvements to the sea ice component of CSM1. The CCSM2 Sea Ice Model (CSIM) satisfies or exceeds all of those recommendations, representing a major improvement over the previous version. Highlights include a rheology that uses an elliptical yield curve and an ice thickness distribution with five thickness categories, which resolve newly formed, first-year, consolidated, multiyear, and ridged ice. The model uses a two-dimensional domain decomposition and time-split thermodynamics and dynamics for efficient parallel performance. The code is written using standard message passing interface (MPI) and Fortran 90 constructs and runs efficiently on several computer platforms.

The CSM1 sea ice model had one thickness category with thermodynamics based on a simple three-layer model and dynamics using a cavitating fluid rheology. Initial CSM1 coupled experiments resulted in some significant biases in arctic ice thickness. The PCWG identified a number of areas of needed improvement in the sea ice model. All of the following were implemented in CCSM2:

- an elastic-viscous-plastic rheology with an elliptical yield curve, incorporating metric terms that take into account grid curvature
- an energy-conserving thermodynamic model that represents the effects of brine pockets through temperature and salinity-dependent energy of melting
- a Lagrangian ice thickness distribution with incremental linear remapping transfer schemes and energy-based ridging and ice strength
- other improved physics parameterizations, including the surface albedo over sea ice, ocean heat flux to the bottom of the ice, a lateral/basal melt formulation, penetrating short-wave radiation in two spectral bands, and corrected parameters for calculating saturation vapor pressure over ice
- second-order horizontal advection (Multi-dimensional Positive Definite Advection Transport Algorithm, or MPDATA)
- an ice model on the same (displaced pole) grid as the ocean model
- an efficient parallel version of the model (MPI)

- improvements for accuracy, efficiency, and bug elimination, and to bring the model into compliance with the emerging CCSM2 standards and conventions
- enhancements, such as a slab ocean mixed-layer model, for partially coupled configurations, including an active-ice-only framework for testing

The sea ice model can be configured to run with one or more of the other CCSM2 component models. The default configuration is the fully coupled model with active atmosphere, ice, land, and ocean components communicating through the coupler. In this configuration the mean arctic sea ice extent is in good agreement with observations, but the mean thickness is lower than observed and the amplitude of the annual cycles of ice amount is larger than observed (see Figures 6 and 7). The transport of ice and water volume through the Fram Strait is within about 30% of the observational estimates. Simulated Antarctic mean ice extent and thickness are somewhat too large and exhibit a slight upward trend over time.

The climate variability simulated by CCSM2 at high latitudes is qualitatively similar to observations. The spatial patterns of CCSM2 surface temperature and precipitation anomalies regressed on CCSM2's NAO index are qualitatively reasonable, as are the anomalies of ice concentration and thickness in the arctic. Southern Hemisphere patterns of variability in the ice compare well to observations and are tied to interesting patterns in the atmosphere and ocean, including ENSO and the Southern Annular Mode. In ice-only simulations that are forced with observational data and coupled to a slab ocean mixed-layer model, realistic sea ice simulations are obtained. Both the ice area and thickness compare well to observations. Additionally, the sea ice trends and variability over the last several decades are reasonably simulated. The model runs very quickly in this active-ice-only framework, providing a very useful tool for testing ice model physics. It also allows for the analysis of the simulated response of sea ice conditions to external forcing, including atmospheric conditions specified from observations or re-analysis data. In addition, a "prescribed-ice" model configuration is available that uses a prescribed concentration in the ice model with an active atmosphere and land model and the data ocean. This configuration provides a means of tuning the atmosphere model or doing atmosphere-only simulations.

The PCWG is developing a set of numerical tests to examine the model's performance with regard to both simulation skill and computational efficiency. This test suite will be used to evaluate proposed changes to CSIM in comparison with current versions of the code. The current effort to implement and test an incremental remapping algorithm for horizontal advection—similar to that used for the ice thickness distribution—is nearing completion. The remapping scheme is second-order accurate and positive definite (like MPDATA, the other supported advection scheme), more efficient for multiple tracers, and monotone (unlike MPDATA).

The PCWG has suggested a number of directions for CSIM development. These include, in no particular order:

- exchange of brine between ice and ocean
- ice rafting
- pancake ice growth
- enhanced melt and mechanical disintegration of ridges/keels
- ice-atmosphere heat and momentum flux parameters
- ice-ocean drag formulation
- improve snow-ice formation
- snow distribution, morphology, and optics
- melt ponds
- spectral radiative transfer through ice
- anisotropy near coasts

e. The Coupler

The CCSM is a framework that divides the complete climate system into component models connected by a coupler. In the current design the coupler is the hub that connects four component models: atmosphere, land, ocean, and sea ice. The coupler has several key functions within the CCSM framework: it allows the system to be broken down into component models that are "plugged into" the coupler, it controls the execution and time evolution of the complete system, and it computes certain interfacial fluxes. Coupler computations include some flux calculations, mapping, run-time diagnostics, and diagnostic data files.

The CCSM coupler has been under continuous development for about a decade. The first publicly released version, coupler version 3 (CPL3), was released with CSM1 in 1996. The latest released version is version 5 (CPL5), which was released with CCSM2 in 2002.

Coupler versions 3 through 5 reflect a design that was originally targeted for shared memory and vector architectures. In particular, they are shared memory applications parallelized using OpenMP directives. While in recent years CPL5 has been ported to distributed shared memory machines (e.g., SGI, IBM, DEC), there is concern that this design may cause the coupler to become a bottleneck to CCSM performance in the near future. A number of performance enhancements found in CPL5 include improved cache performance and scaling for the mapping computations, improved communication performance between the coupler and the ice model by means of data packing, and improved cache usage in the subroutines doing time averages. Additional changes were made in the number and types of fields that are exchanged between the coupler and components. Changes were also made to improve mapping of vector fields around the North Pole between the atmosphere and ocean models.

In both CSM1 and CCSM2, there are only two horizontal grids: a grid shared by the atmosphere and land models and a finer grid shared by the ocean and sea ice models. Ideally each CCSM component would be able to specify its own horizontal grid. This option was explored early in the development of CSM1, but it was abandoned because of the complexities involved in ensuring conservation of exchanged properties and potential pathologies, such as sea ice being modeled where there was no ocean. The solution adopted and carried forth in CCSM2 was to require that the ocean and sea ice models share the same grid and land mask. Since all ocean/ice grid points are either fully ocean or fully land, this mask effectively defines the coastline of the coupled system. Similarly, coupling issues between the land and atmosphere were greatly simplified by requiring that these components share a common horizontal grid. For each element of this grid, an associated land fraction is determined from the overlap with the ocean/ice grid and mask.

The ocean/ice mask includes all bodies of salt water, but it distinguishes as marginal seas those that are dynamically isolated from the major oceans, such as the Caspian Sea. It masks as land fresh water lakes, such as the Great Lakes, and unresolved marginal seas, such as the Persian Gulf in some configurations. The rationale behind this partitioning was to keep an equation of state for salt water and sea ice formation exclusively in the ocean model. Since in CSM1 ocean calculations were performed in latitudinal slabs, there was no computational penalty for not partitioning; such is not the case in CCSM2. The land model needs only to consider the much simpler fresh water equation of state and ice formation when its specification of land surface type indicates a lake.

Since the land model cannot know *a priori* exactly where coastlines, including islands, will be, it must be prepared to be active anywhere. Therefore, all land data sets should be global. However, the river runoff scheme did not follow this principle, and ad hoc procedures were adopted in CCSM2 to deliver river runoff from the heads of some estuaries to the coast as defined by the ocean/ice grid. These were not required in CSM1, because it did not have an explicit runoff scheme. In the future, more realistic coastlines could be realized by allowing the ocean/ice grid cells to be partially land, or by embedding much finer resolution ocean models along some coasts where the added computational expense is deemed worthwhile (see Section VII.g).

In a change new to CCSM2 (CPL5 and CPL6, discussed more fully in the next section), the matrices used by the coupler to map variables and fluxes from the atmosphere grid to the ocean grid and vice versa are computed offline using a scheme obtained from LANL. The mapping files need to be computed once for each new ocean/land mask. The coupler then uses these mapping files as well as the details of their creation. A mapping and its inverse are computed offline for each different land/ocean mask and grid combination and for both a bilinear interpolation and an area-conserving scheme. There is a test and checking procedure that involves checking for negative values and then mapping a test pattern and checking for large errors. In addition, upon starting the coupler performs some checks on the mapping files. Particular attention was needed along the "180° longitude" line emanating from the displaced POP ocean/ice northern pole towards the vicinity of the geographical pole. To avoid a singularity, the POP ocean/ice grid must not have a point exactly on the geographical pole.

The coupling between model components is accomplished through property exchanges (fluxes) across model interfaces. It was originally envisaged that all these fluxes be computed centrally in the coupler code and conservatively distributed to components. The exceptions in CSM1 were the atmospheric radiation, because of the requirement for three-dimensional data sets, and the turbulent atmosphere-land fluxes, because their computation is complex and the main task of a land model. However, the coupler was and still is responsible for merging the surface albedos and for ensuring conservation. Each of the multiple ice categories of the CCSM2 sea ice model requires its own flux calculation from a multitude of parameters. In CCSM2 these calculations were improved and transferred to the sea ice model along with the merging of ocean-ice and atmosphere-ice fluxes. The turbulent atmosphere-land fluxes were also improved but remain in the land model. The coupler now only computes turbulent ocean-atmosphere fluxes of heat, evaporation, and momentum in much the same way as in CSM1, except the bulk turbulent flux formulas now use the vector difference between the wind and the ocean surface currents, instead of just the wind alone. Air-sea gas exchange is to be computed in the ocean model, but it presently uses a wind speed derived from vector averaged stresses, which introduces an error that increases with wind variability. Using a properly averaged wind speed passed from the coupler will eliminate this problem.

The frequency at which model components are coupled varies depending on the physics requirements. The large diurnal cycle in atmosphere-land and atmosphere-ice fluxes dictates that the atmosphere be coupled to both of these other components every time step, except radiative fluxes that are computed hourly in CCSM2 (only every three hours in CSM1). The large heat capacity of the ocean means its diurnal cycle is less important, so the atmosphere-ocean coupling frequency is one day in both CSM1 and CCSM2. Another consideration is that the time stepping of the ocean model (the occurrence of averaging time steps) is tied to the coupling with the atmosphere. Nonetheless, as other aspects of the coupled model improve, the effects of more frequent coupling should be explored.

While CPL5 was being prepared for the CCSM2.0 release, a new project began to design and build a new coupler, version 6 (CPL6). The goals for CPL6 include improved performance, portability, and scalability by selecting a distributed memory design. CPL6 was developed through collaboration between NCAR and the DOE's Argonne National Laboratory. The DOE Lawrence Berkeley National Laboratory also helped by developing a flexible message-passing handshake library. The project started with a requirements analysis and prototyping followed by architecture design. Argonne's primary role was to develop a lower-level coupling layer suited to CCSM's coupling requirements. This model coupling toolkit (MCT) library was developed at Argonne, has been released to the general public, and is at the heart of CPL6. NCAR's primary role was to develop the higher-level design and functionality appropriate for CCSM. CPL6 is currently being validated within CCSM and will be included in the next release of CCSM2. Initial performance tests suggest that CPL6 will scale well to many more processors than CPL5 and that there is a significant improvement in communication and mapping performance compared to CPL5 on the same number of processors. CPL6 also provides improvements in flexibility and extensibility. For instance, it is relatively easy to add new fields that need to be coupled, which will facilitate the addition of biogeochemistry fields in the future. There is also more flexibility for exchanging fields at different time intervals, the ability to move coupler work to different sets of processors, and the ability to change the coupler's decomposition, all of which can enhance performance.

Discussions are already under way to plan for coupler version 7. There is a desire within the CCSM community to trivially instantiate either single or multiple executable versions of CCSM running serially, concurrently, or a combination of the two. This will present significant challenges, but CPL6 has been designed with this possible future requirement in mind.

f. Software Engineering Aspects

Over the past few years, there has been increased recognition that software engineering is an important aspect of the CCSM project. In 1999, the CCSM Software Engineering Working Group (SEWG) was formed on the same basis as the other working groups in the CCSM program. The SEWG serves to bring the broader software engineering community together through regular meetings and actively works to coordinate DOE, NASA, NOAA, and NSF efforts. The SEWG meetings also provide opportunities for new individuals to meet and interact with the CCSM community, to present new ideas or opportunities, and to initiate new collaborations. One such collaboration is with the Common Component Architecture (CCA) project, a broad DOE effort to develop a standard for exchanging scientific components. The CCSM is exploring ways to use the CCA for component exchange in the CLM.

This group serves to bring the climate modeling community together to discuss software engineering issues specifically related to the CCSM program. The SEWG was instrumental in the development of the CCSM Developer's Guide, as well as education and training specifically geared toward software engineering process improvement. The SEWG also urged the formation of a software engineering support group and, in 2001, CGD established CSEG. A manager supervises this group of support people with oversight by the chairman of the SSC.

Formally, CSEG is a separate group within CGD composed mostly of software engineering support people. CSEG is primarily responsible for CCSM software engineering maintenance and development of models and data management tools of the CCSM program. It also provides support for specific aspects of the overall CCSM infrastructure, such as build and run procedures. CSEG has taken the lead on porting of CCSM code, releases, maintenance of releases, and support. It also coordinated the releases of CCSM2.0 in May 2001 and CCSM2.0.1 in October 2001. These releases required that all model changes be coordinated and eventually frozen, that the model be extensively tested in several configurations, that long control simulations be carried out with scientific oversight, that documentation be written and reviewed, that both input and output data sets be pulled together and inspected, and that a public Web page be generated and made available at release time. CSEG is responsible for supporting the releases by answering user questions, regularly testing the model on supported platforms, porting to new platforms, and releasing patches to fix problems.

The coordination of software engineering in CCSM has improved significantly in the last two years. There is a software engineering liaison person for each active CCSM component model, and there are weekly meetings of CCSM programmers to discuss plans and coordinate tasks. Software engineering liaison persons also coordinate many of the activities associated with development of the active model components. CSEG currently has responsibility for maintenance and development of all aspects of the CCSM coupler component. There has also been a recent software rewrite of CLM to implement significant improvements in ease of use and flexibility for future model development efforts.

A new graphical user interface (GUI) was included in the CCSM2.0 to assist users in generating CCSM cases, and work is under way to develop a new and much improved GUI for building model cases. The CSEG manages the Concurrent Versioning System (CVS) repository, maintains a log of CCSM experiments, and manages bug reports. There is a formal procedure for requesting access to the CCSM CVS repository, and there are procedures for working within the repository, for testing changes, for requesting that changes be formally adopted in a component, and for coordinating those changes. CRBs are being put in place for individual components where needed and for the overall CCSM to coordinate code changes and prioritize and review those changes. There is a plan to place documents under CVS control, and Web pages are being developed to give the community easy access to those documents. There is also an effort to explore ways to use databases, the Web, and other software tools to improve coordination and communication within CCSM.

There has been an effort over the last few years to improve the productivity, quality, and coordination of model development activities. In 2001, the CCSM project received a grant from NSF to pay for software engineering training. In December 2001, a consultant was hired to provide three days of training on software process improvement. This training, in conjunction with weekly brown bag discussions and reading, has had a large impact on the way software engineers work in CCSM. CCSM software projects are now developing a formal process for carrying out work that includes developing requirements, design, and formal test plans. Experience with this formal process is limited, and CCSM is constantly evaluating the relevance and impact of these processes, but this could ultimately have a large impact on both the quality of model development, as well as the productivity of the software engineering support staff. CCSM plans to pursue additional training opportunities for software engineers as the need arises.

There are many software engineering tasks and issues that will be addressed in the future. CCSM is an active participant in NASA’s Earth System Modeling Framework (ESMF) project. Incorporation and use of the ESMF will likely require changes to many aspects of the CCSM component models and the development of a new structure for coupling models. The potential benefits of using ESMF are significant and include increased performance, flexibility in coupling strategy, and robust, shared utilities. The DOE Scientific Discovery through Advanced Computing (SciDAC) project provides significant resources for CCSM software engineering development. This effort has already resulted in significant improvements to the CCSM coupler through collaborative development of CPL6 and to CAM2 by separating dynamics and physics, significantly improving the performance of CAM2 coupling to surface models, and by “chunking” the physics to improve the cache performance in the model. Efforts such as these will continue as part of the DOE SciDAC collaboration and will be coordinated largely by the CCSM SEWG.

Other software engineering issues that will be addressed in the future include improved testing of the model to increase quality and reliability, continued assessment of model performance and tuning, and code rework to provide increased flexibility and usability of the models. In 2003, a rewrite of CAM2 will begin to address these issues. Also in 2003, a new version of the ocean model will be incorporated and tested within CCSM. The models are also being modified to allow addition of biogeochemistry science with relative ease. There will be a continuous effort to increase code reuse by relying on shared code to serve all component models in areas like system calls, performance monitors, calendars, and interpolation routines. Much of this code will be supplied through collaborations such as SciDAC and ESMF.

As new hardware becomes available, assessment, porting, and performance tuning will be important. Currently, CCSM is designed for distributed shared memory architectures like the IBM, and ports have already occurred to the latest IBM Power4 architectures. IBM, SGI, and HP/Compaq continue to be the primary target platforms. Work has begun on porting CCSM2 to Linux platforms as it becomes an increasingly viable alternative. In addition, if hardware like the NEC SX-6 or Cray X1 becomes viable for running CCSM2, significant efforts may be required to efficiently use these architectures. The overriding goal of the CCSM software engineering effort over the next five years is to better support scientific model development through improved software and tools, growth in software engineering staff skills, systematic and coordinated software development processes, effective resource management, and productive collaborations.

V. Planned Climate Experiments

The scientific objectives of the CCSM program include the use of the CCSM products to investigate both scientific questions of a basic nature and those that are anticipated to be useful for the provision of information in support of decision-making. This section describes the present plans to use the products of the program in this regard.

a. Applied Climate Modeling with the CCSM2

At the Conference of the Parties meeting in Delhi, many nations came to recognize that adaptation to climate change might be more expedient than mitigation. When mitigation was a priority, there was the perception that once climate models had raised the issue of the effects of climate change due to anthropogenic forcing, the policymakers would heed this general warning and devise mitigation strategies. According to this line of reasoning, after the mitigation strategies were initiated, the climate change simulations from the climate models would be of less interest. However, it is now clear that adaptation to climate change is a matter of high priority, and accordingly, climate models will be asked for even more detailed and reliable regional climate change information. In effect, since the people of the world must adapt to climate change, it is more important than ever for the climate models to provide detailed projections of future climate so that people will have more detailed and accurate information concerning the conditions to which they must adapt. In addition, there needs to be developed a better sense of the reliability of the projections so that potential mitigation strategies can be evaluated.

For these reasons, the CCSM program will undertake a suite of extensive simulations and analyses directed towards elucidating some of the important questions that have been raised in the context of the ongoing IPCC and the CCSP assessment activities. The simulations will be carried out using the various tools that are available in the CCSM program as a result of different configurations of the components of the CCSM. The main themes of these questions are climate sensitivity to physical processes, estimates of overall reliability, and projections of important global and regional changes in climate.

The following questions relate to climate sensitivity to physical processes.

- What are the primary forcing factors of Earth's system, and how do changes in atmospheric constituents and solar radiation drive global climate?
- What are the sign and the nature of the climate feedbacks of future climate change when aerosols are included explicitly in a global coupled climate model?
- What are the factors that affect climate sensitivity?
- What are the sign and nature of the feedbacks of future climate change when a fully coupled carbon cycle is included in a global coupled climate model?
- What are the effects of changes in global land cover and land use?

This group of questions will be addressed through the analysis and study of sensitivity runs with CAM coupled with a slab ocean model and 20th century simulations using CCSM2 at T85 forced by sulfate aerosol (both direct and indirect), black carbon, and mineral dust. Ensemble runs with single and various combinations of forcing factors will be carried out with the Parallel Climate Model (PCM) and compared with CCSM2 T85 to check for consistency. Five member ensemble runs will be carried out with the fully coupled carbon cycle in CSM1 for the 20th and 21st centuries. Land use change experiments with PCM for specified time periods and T85 CCSM2 experiments with land use change, urbanization, and soil degradation will be conducted and comparative analysis carried out.

The following questions relate to the overall reliability of climate model results.

- What are the effects of atmospheric resolution in a global coupled model on present-day climate simulation and future climate change?
- How can we better quantify uncertainty of climate change projections?

- How does the climate sensitivity vary with different models and configurations?
- What are the effects of scenario uncertainty in projections of climate change?

This group of questions will be tackled through the analysis and study of an extensive suite of results from different models, different resolutions, and different greenhouse gas scenarios. In particular, much more detailed simulations of regional climate will be obtained from improvements in the representation of geography and topography by integrating CCSM2 at resolutions at least twice that of CSM1. CCSM2 will be integrated in fully coupled configuration at T42, T85, and T107 using 20th century forcing factors and IPCC scenarios A2 and B2 (IPCC, 2001). The control runs will be a minimum of 100 years for the T107 and a few hundred years minimum for the T85 and T42. Ensembles will have at least five members. There will also be several time slice experiments at T239.

Comparison will be made of 1% CO_2 runs with different model versions and resolutions including results from CSM1, PCM, Parallel Climate Transition Model (PCTM), and CCSM2 at T42 and T85 to gain insight into the variability of climate sensitivity. Lastly, 21st century climate change simulations with CCSM at T85 for IPCC scenarios A2, B2, A1FI, A1B, and B1 will be conducted (IPCC, 2001). There will be single realizations for the last three scenarios and five member ensembles with the first two.

The suite of climate simulations described above will also be analyzed and studied to obtain projections of important regional climate phenomena. Some of the questions that will be addressed are as follows:

- How will ENSO, monsoons, and modes of extratropical variability (Antarctic Oscillation, NAO, storm tracks) change in a future climate in relation to long-term changes in base state or other mechanisms?
- How do changes of the base state of future climate affect modes of decadal variability, and how could decadal variability mechanisms be effected by or interact with external forcing changes (e.g., the mid-1970s change)?
- How will weather and climate extremes change in the future?
- How will global temperature, precipitation, evaporation, and the cycling of water change in a future climate?
- How is global sea level affected by climate change?
- Will Arctic Ocean sea ice begin to seasonally disappear?

This program of applied climate modeling is extensive and will place great demands on computer time and storage. Table 2 gives an estimate of the computer time and storage required to carry out the runs necessary to conduct this program. Even more critical is to get a much larger participation by the scientific community in the analysis and interpretation of these results to maximize the return on the investment.

Table 2. Estimate of computer time and storage needed to conduct the CCSM program in applied climate.

	Kilohours of CPU	Terabytes of Storage
Sensitivity Runs	6,747	167
Reliability Runs	11,659	271
Regional Projection Runs	1,101	28
Total	19,507	466

b. Experiments to Elucidate the Mechanisms of Thermohaline Circulation Changes

One of the most fascinating questions that has received considerable attention over the past 5 to 10 years is that of potential changes of the Meridional Overturning Circulation (MOC) in the North Atlantic Ocean. This MOC (or thermohaline circulation) is a crucial aspect of the climate system that produces relatively mild (as measured by latitude) conditions in Western Europe. Some climate change experiments have suggested that the MOC is changed under a climate warming scenario because of changes in the ocean temperatures but also because of changes in fresh water flux into the North Atlantic. The Working Group on Coupled Models of the World Climate Research Programme (WCRP) organized a project under the auspices of the Coupled Model Intercomparison Project (CMIP) to conduct coordinated experiments to run different climate system models under different hypothetical scenarios of fresh water flux in the North Atlantic and then compare and contrast the model simulations as to the nature and rates of response of the MOC.

The first such coordinated experiment addresses the issue of the possible slowdown and recovery of the MOC in the North Atlantic that could result from an anomalous input of fresh water. The response is being tested using CCSM2 by first putting 0.1 Sv of fresh water into the North Atlantic from 50°N to 70°N for 100 years, which stabilizes and slows down the MOC, and then turning off that anomalous fresh water input and running the model for 100 additional years to gauge the recovery of the MOC. Additional experiments will use the "partial coupling" technique whereby a control run is performed but with input of the fresh water flux from a 1% CO_2 increase run in the North Atlantic, and a 1% CO_2 increase run where the fresh water flux from the control run is input to the North Atlantic. These experiments are meant to test the relative contributions of heating of the surface layers or the changes in fresh water flux to changes in the strength of the MOC. The results of these experiments will be analyzed and compared with results obtained by other groups around the world in order to gain a better understanding of the variation in sensitivity to this process. These studies should be helpful in assessing the risk of abrupt climate change, particularly on a regional basis.

c. Biogeochemistry and Ecosystem Dynamics

Considerable research effort is now under way within the CCSM program to unravel the complex interactions and feedbacks among climate, atmospheric chemistry, biogeochemistry, and ecosystem dynamics under past, present, and potential future conditions. A core activity of the CCSM BGCWG is the development, evaluation, and application of fully interactive climate-carbon simulations. The objectives are to better understand what processes and feedbacks are most important in setting concentrations of atmospheric CO_2 and how the CO_2 growth rate and climate change may co-evolve in the future. The choice for an initial focus on carbon was based on the primary role of anthropogenic CO_2 emissions in potential climate change, the availability of a global network for the measurement of atmospheric CO_2 and related compounds, and the readiness of the various biogeochemical component models for the ocean, atmosphere, and land.

The BGCWG has outlined a suite of multicentury carbon-climate control and CO_2 emission scenario simulations. The strategy is to build on the understanding of carbon-climate interactions systematically, progressing with experiments/hypotheses that can be evaluated by ancillary information (e.g., on interannual timescales) to experiments that project the future interactions in the carbon-climate space that Earth has not experienced in the past 400,000 years. Key to this analysis will be sensitivity experiments that capture the scientific uncertainties in the representation of the processes. The simulations are already under way in a recently constructed, fully interactive CSM1 climate-carbon model version, which is based on relatively simple ocean and land biogeochemical dynamics. Those results are also being rapidly migrated to CCSM2 and merged with more sophisticated marine and terrestrial ecological and biogeochemical models currently under development.

The land and ocean carbon cycle components in CSM1 (carbon) are based on the NCAR LSM and CASA (Carnegie-Ames-Stanford Approach) model (Potter et al., 1993; Bonan, 1998) and the Ocean Carbon Model Intercomparison Project (OCMIP-II) (Doney et al., 2001) biogeochemical models, respectively. Simulated net primary production (NPP) on land is computed as the difference between gross primary production provided by LSM, thus linking carbon uptake and stomatal water loss, and autotrophic respiration. NPP is allocated to three biomass pools (leaf, wood, root), and heterotrophic respiration and detrital material are incorporated through two soil carbon pools. Prognostic leaf phenology and dynamic allocation of NPP are also incorporated. The ocean biogeochemical model includes, in simplified form, the main processes for the solubility carbon pump, organic and inorganic biological carbon pumps, and air-sea CO_2 flux. The model has been modified from the original OCMIP-II version so that new/export production is computed prognostically as a function of light, temperature, phosphate, and iron concentrations. A dynamical iron cycle has also been added. The CSM1 atmospheric model has been modified to transport a radiatively active CO_2 tracer.

The enhancements under way for the CCSM2 (carbon) model incorporate key dynamical processes that are hypothesized to be important for paleoclimate and anthropogenic climate change. For the land model, CLM2, a new code structure facilitates the hierarchical incorporation of different landscape elements (e.g., glaciers, lakes, natural vegetation, urban), age classes, and multiple competing PFTs. Other improvements planned include a more advanced treatment of prognostic phenology, a dynamic nitrogen cycle and carbon-nitrogen coupling, and multiple agricultural PFTs. On the ocean side, modifications involve adding a multinutrient (N, P, Si, Fe) and phytoplankton functional group (picoplankton, diatoms, calcifiers, nitrogen-fixing diazotrophs) ecosystem model (Moore et al., 2002), a more sophisticated dynamic iron cycle, and a particle ballast model for treatment of the vertical particle sinking flux and remineralization.

Preliminary multicentury control integrations of the ocean-atmosphere and land-atmosphere versions of the CSM1.4 coupled carbon-climate model have been completed, and a set of five multicentury control and emission scenario experiments are under way with the fully coupled system. As a first step, a 1000-year control integration will be run with a closed global carbon cycle to quantify the natural interannual to centennial variability in carbon exchange within and among the reservoirs, as well as to document the long-term model drift. Four 400-year perturbation experiments for the period 1870–2250 then will be run branching from the control integration. In one pair of simulations, atmospheric CO_2 will be prescribed following the trajectory of one of the IPCC scenarios and the uptake by the ocean and land determined, the sum of which equals the total permissible emissions. The difference between the two runs will be in whether the increasing atmospheric CO_2 effects the radiation and thus climate (i.e., uptake under fixed or changing climate). For the second pair of runs, the CO_2 fossil fuel emissions will be specified rather than the atmospheric concentration, and the growth in the concentration of atmospheric CO_2 will be computed. The emissions scenarios will also be run with and without the climate-radiative CO_2 feedbacks. A set of sensitivity studies will also be conducted to better elucidate the mechanisms behind the observed behavior of the perturbation runs (modifying the terrestrial CO_2 fertilization, ocean dust deposition, etc.). The CCSM carbon-climate results will be an important contribution to the IPCC Fourth Assessment Report. These so-called "Flying Leap Experiments" have become the basis for the common protocols for the international Coupled Carbon Cycle Climate Model Intercomparison Project (C4MIP; http://www.atmos.berkeley.edu/c4mip/) a joint effort of the WCRP and International Geosphere-Biosphere Program (IGBP).

d. The Climate of the Last Millennium

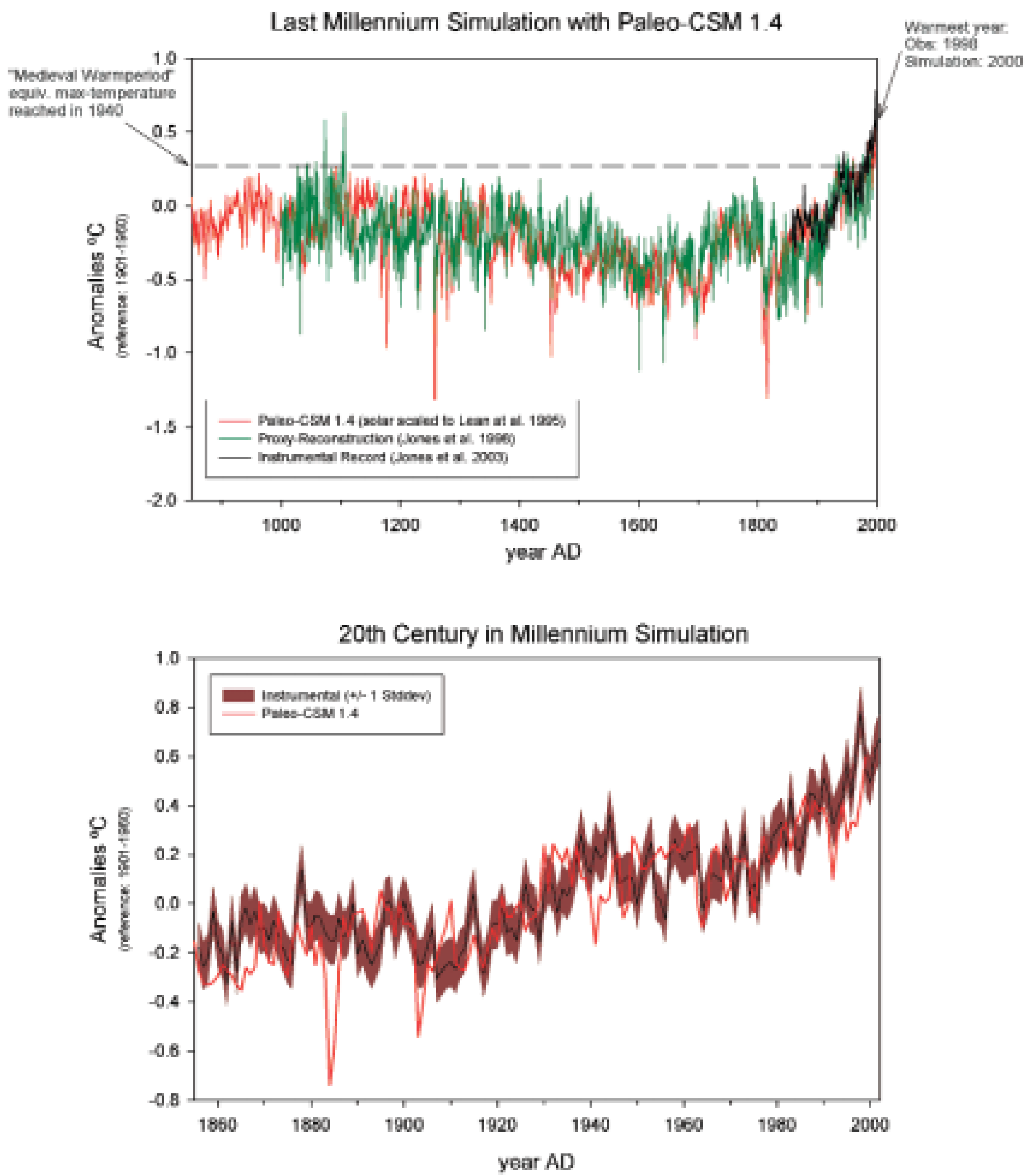
The instrumental record back to 1850 AD is too short to evaluate the full range and timescales of natural climate variability. Yet, knowledge of the magnitude and spatial expression of internal climate variations together with externally (but naturally) forced variability is crucial for our understanding of future climate changes, including the evaluation of climate sensitivity. Significant progress in collection, calibration, and interpretation of climate proxy data covering the last millennium has resulted in new climate reconstructions with significantly higher temporal and spatial resolution. This high data density now available for a number of areas around the globe offers an important test bed for climate models to verify the various proposed mechanisms for climate changes. In addition, recent research has detected possible mechanisms linking natural forcing factors, such as solar irradiance changes and influence from volcanic aerosol loading, to the temporal variations of some of the internal modes of climate. While more simple models can be used to study changes to Earth's energy balance, only coupled models such as CCSM2 are able to simulate these more complex dynamical processes. Analysis of simulations of the past millennium can now also include a significant spatial component.

Solar irradiance changes on the order of 0.1% have been measured for individual sunspot cycles. Over the last millennium, when sunspots disappeared for a long period of time, such as the Maunder Minimum (1645–1715 AD), the estimated change was larger at 0.2–0.5%. Although considerable uncertainty exists for solar irradiance reconstructions on these longer timescales, simulations with several of these reconstructions allow us to fingerprint their influence and bracket the sensitivity of CCSM models. Most previous climate model simulations for the last millennium have used volcanic forcing data that have no seasonal variation and that are uniform with latitude. CSM1 and CCSM2 runs at NCAR now will allow for the individual evolution of volcanic aerosols in the lower stratosphere and take into account the latitudinal location of the volcanic eruption. Although volcanic forcing has traditionally been thought to influence climates only on short timescales, close temporal spacing between eruptions will force a more prolonged signal. CCSM2 simulations will look at the magnitude and regional forcing of climate due to individual and groups of volcanic eruptions.

A coupled simulation of the last millennium was recently completed by C. Ammann (NCAR) and F. Joos (University of Bern, Switzerland) using the CSM1.4 paleoclimate version. The simulation used ice core derived greenhouse gas histories, a recurring natural tropospheric aerosol cycle, solar irradiance based on a Beryllium–10 record (Bard et al., 2000) scaled to match low-frequency variations of Lean et al. (1995), and a new ice core based volcanic aerosol data set expanded from Ammann et al. (2003). In Figure 16, a time series of the globally averaged annual surface temperature anomalies is plotted for this simulation and compared to the multiproxy-based reconstruction (Jones et al., 1998), as well as the instrumental record (Jones and Moberg, 2003). The lower part of the figure shows the 20th century portion of the simulation compared to the instrumental record with one standard deviation error bar.

The simulation indicates that radiative perturbations from external forcing have played an important role in natural climate variability. Contributions from increased solar irradiance and lack of explosive volcanism explain most of the early 20th century warming, whereas the warming in the late 20th century is likely due to radiative forcing from anthropogenic sources (Ammann et al., 2003). There seems to be good agreement between the simulated and reconstructed climate in terms of the overall trends, as well as in multidecadal structure. However, experimentation to simulate climate of the last millennium is only beginning. Other components, such as land use changes and changing vegetation together with alternative forcing series, will have to be included.

Figure 16. Time series of globally averaged surface temperature anomalies for the millennium simulation using CSM1.4 and the actual values as estimated by proxy reconstruction and the instrument record, when available. The lower part of the figure is the 20th century portion of the upper time series on an expanded scale.



The planned series of CCSM2 simulations for the last millennium (and particularly the last 300 to 400 years) will also be used to study the forced and unforced variations in important internal modes of climate, such as ENSO, NAO, sea ice, North Atlantic overturning, etc. Their contribution to climate understanding could be substantial, in particular for extreme conditions such as droughts. These simulations will be used to enhance the understanding of the mechanisms for the warmth of the 20th century as compared to earlier centuries and provide a more complete context for analyzing and interpreting projections of future climate change resulting from human activities.

e. Predictability of the Coupled Climate System

The most compelling reasons for examining the predictability and the experimental predictive skill of CCSM2 are to determine which natural phenomena are, in principle, reproducible by the model and then ascertain the ability of CCSM2 to reproduce such phenomena. These issues relate directly to our understanding of the predictability and predictable dynamics of the climate system, which is of both theoretical and practical interest and as yet poorly understood. Some examples of natural phenomena of which our knowledge is insufficient to confidently determine their intrinsic predictability are:

- decadal flow regime variations, such as that which occurred in the late 1970s
- decadal drought cycles, such as that which occurred in the dust bowl of the 1930s
- variations in the interrelationships of interannual cycles, such as the Indian monsoon–ENSO correlation

At present, it is unknown whether any of these phenomena is predictable on the timescales of their variation. A comprehensive climate system model, such as CCSM2, can be invaluable in improving our understanding of predictability limits of these phenomena. If we assume that the model in question is able to reproduce the temporal evolution of the natural system with nearly the same fidelity with which the model can reproduce a perturbed version of itself, then the predictability of the climate system can be deduced from component and coupled model twin experiments (e.g., Gent and Tribbia, 1993; Chang et al., 2003; Shukla et al., 2000). In this experimental setting, the prediction is verified against the simulation of the same model. The predictive skill of the model gives an indication of the intrinsic predictability of the climate system within the realm of the given model. Several modeling centers, including GFDL (Griffies and Bryan, 1997) and the Hadley Centre (Collins and Allen, 2002), have used these types of experiments to study the potential predictability associated with certain climate phenomena on seasonal-to-decadal timescales in different parts of the world. Similar experiments should be carried out with CCSM2 to gain an understanding of the intrinsic predictability of this model.

In principle, the information derived from the twin experiments is not useful if the predictive skill of the model is poor and the model is not able to replicate spatial and temporal characteristics of natural phenomena. There is, nonetheless, important information in the inability of the coupled model to adequately reproduce the temporal evolution of the natural climate system. That lack allows us to examine and diagnose the deficiencies in the coupled simulation from a different perspective. To this end, it may be particularly useful to conduct intercomparison studies of twin experiments among different coupled models.

Apart from the scientific issue of intrinsic predictability, there are more practical issues concerning the predictive skill displayed by CCSM2 in forecasting the observed climate variability in nature. The study of this practical issue requires conducting prediction experiments with observed initial conditions and gauging the validity of the predictions against observations. A particularly useful experiment is the prediction of an ensemble of ENSO events. These predictions can be initialized from the existing ocean data assimilation (ODA) products, such as those from the recently completed Applied Research Centers' International Research Institute for climate prediction (IRI) project. Not only can this experiment provide an evaluation of the predictive skill of CCSM2 in seasonal climate forecasts, but more importantly, it can permit the diagnosis of the evolution of physical biases in the coupled system. This can result in a better understanding of the chronic problems that affect most coupled models in the tropical region. ENSO events are useful because of their relatively high frequency of occurrence, the strength of the signal, and strongly coupled variability. Less frequent events, such as the decadal regime changes and drought cycles referred to above, will be a challenge not only for the historical initialization of the climate system in the 1930s and 1970s but also for the capability of CCSM2 to retain the decadal timescale signature of these events. Such decadal timescale studies will be of additional use in diagnosing and assisting in the remediation of model deficiencies.

VI. The Near-Term Program for Understanding the Behavior of the Coupled Model

The extensive integrations of the CCSM2 produced a climate simulation that had many new successes, some persistent challenges, and a couple of new challenges. These results stimulated a vigorous research program directed to understand how the various interactions of the physical and dynamical processes represented in the model resulted in the behavior simulated. This section describes the approach taken and results obtained, so far, in this endeavor. The investigations have moved along three axes: biases, sensitivity, and variability. The intention is to use the knowledge gained in this work to modify the component models and the coupler in order to produce the best possible simulation tool to be applied in the applied climate modeling mode for input to the IPCC Fourth Assessment Report. Better understanding of the causes of differences in climate sensitivity and variability are also expected to be very valuable to the assessment process.

a. Investigation of the Physical Basis of Biases in the CCSM2 Simulations

The tropics are regions of strong ocean-atmosphere interaction on seasonal, interannual, and possibly longer timescales. An accurate representation of the mean climate, its annual cycle, and variability of the tropical coupled system has a profound impact not only on a model's ability to simulate and predict natural climate variability but also on a model climate's sensitivity to external forcing. Therefore, a realistic simulation of observed tropical behavior provides an important measure of a climate model's performance and has always been an important aspect in the development of coupled climate models.

Achieving realistic simulations of the tropical climate system has been an enormous challenge for the coupled modeling community. In spite of recent advances in climate model development, virtually all climate models still show significant biases in the tropics, such as the notorious double ITCZ problem mentioned earlier (Davey et al., 2002; Latif et al., 2001; Mechoso et al., 1995). The bias problems reflect, in part, the central role of subgrid-scale diabatic processes in the tropics that have proven difficult to parameterize, such as turbulent mixing in the atmosphere and ocean, moist convection, and cloud-radiation interaction. The biases also reflect the strongly coupled nature of the tropical system that can amplify small systematic errors in individual component models into large biases in the coupled simulation. In the CCSM program, it is recognized that addressing simulation biases needs to move beyond their study within the context of individual component models. One of the higher priority short-term activities of the CCSM program is a concerted effort to confront and overcome systematic model biases in the tropics on seasonal and longer timescales.

Several factors have been suggested as candidates for causing the bias associated with the ITCZ/cold tongue complex in the tropical Pacific and Atlantic Oceans. One of the leading candidates is regional feedbacks between stratocumulus clouds, surface winds, upwelling, coastal currents, and SST in the cold tongue region, which are poorly represented in many climate models. The stratocumulus clouds are important modulators of climate. They are effective reflectors of short-wave radiation and thus limit the solar radiant energy reaching the ocean surface. In CSM1, subtropical stratocumulus clouds were largely absent, which led to an overestimate in the short-wave radiation over the cold tongue region. This shortcoming has been partially addressed in the CCSM2 by implementing an improved radiation scheme and a prognostic cloud scheme. As a result, the short-wave radiation at the ocean surface has been reduced substantially in CCSM2. This alone, however, has not led to an overall improvement of the simulated ITCZ/cold tongue complex in the model, indicating the complex nature of the problem. A surface heat flux analysis suggests that in spite of the reduction in the short-wave radiation, the net surface heat flux at the ocean surface was not reduced substantially because the reduction in the short-wave radiation is largely offset by a decrease in the latent heat flux, associated with an excessively moist, shallow boundary layer. This suggests the current model physics produce insufficient entrainment of dry air into stratocumulus-capped marine boundary layers. An effort is under way to implement a new boundary layer model into CCSM2 that more realistically represents the interaction of turbulence, moist thermodynamics, and entrainment processes.

Another weakness of the model seems to be associated with the treatment of the steep, high terrain of the Andes. The relatively low resolution of the model poorly represents the steepness and location of this feature, leading to overly weak surface winds off the coast of South America. As a result, the coastal current and upwelling are too weak when compared to observations, contributing to a warm SST bias along the coast.

In addition to the biases in the simulated tropical annual cycle, there are also biases in the simulated interannual variability in the tropics. ENSO-related SST anomalies in the tropical Pacific remain somewhat weak in CCSM2. The spatial structure of the SST anomaly tends to be too narrowly confined near the equator and to extend too far westward when compared to observations. The frequency of the simulated ENSO variability is generally too high. It is not immediately clear whether these variability biases are necessarily related to the double ITCZ problem. However, it is likely that these model biases are linked to the biases in the simulated trade wind variability and to the biases in the upper ocean thermal structure and the associated variability. The former may be attributed to the deficiency in convective parameterizations and boundary layer physics in the atmosphere component, while the latter may be linked to problems in the mixing parameterizations of the equatorial ocean. Another possible source may be related to the weak tropical intraseasonal variability in the model. The intraseasonal variability can act as a stochastic forcing to interannual variability. Further diagnostic and modeling studies are clearly needed to understand the underlying physics of these biases. Ocean dynamics, errors in the albedo of deep tropical convective cloud systems, and biases in cumulus parameterization may also play a role in these deficiencies. A program of diagnostic studies and sensitivity tests aimed at exploring the causes of the biases in the ITCZ/cold tongue complex is under way.

Apart from the above biases inherited from CSM1, a new bias problem emerged in CCSM2. The tropical tropopause in CAM2 is at least 5 K colder than observed, regardless of whether CAM2 is run with observed SSTs or coupled in CCSM. This bias is unfortunate for tropospheric modeling but perhaps not catastrophic. However, for middle atmosphere modeling with chemistry, the tropopause cold bias is a very serious problem. Since the tropical tropopause temperature is the dominant factor controlling the transport of water vapor into the stratosphere, the cold bias in CAM2 results in a dry bias in the middle atmosphere. Water vapor biases cause significant errors in middle atmospheric chemical processes and in the occurrence of polar stratospheric clouds. The cold tropical tropopause did not occur in CCM3, which matched both the observed annual mean and the annual cycle reasonably well.

In CAM2, the tropopause bias is nearly independent of the dynamical core, although the finite volume dynamical core is slightly warmer than the spectral Eulerian or semi-Lagrangian cores when run at 2° x 2.5° resolution or higher. Increasing the vertical resolution also appears to be somewhat helpful in the finite volume dynamical core. Tests have shown that the cold bias was not introduced by a single change in the physical parameterization between CCM3 and CAM2. Instead, several changes reinforced each other, each change independently cooling the tropopause by approximately 1 K. The modifications were changing from diagnostic to prognostic cloud water; moistening the lower troposphere by evaporation of convective precipitation; and changing to a more recent parameterization of the water vapor continuum in long-wave radiation. All of these changes appear to move toward a better representation of atmospheric physics and to result in significant improvements in the simulated state away from the tropopause, suggesting that some other process is missing. It is now believed that the main problem is an inadequate representation of ice processes in both the convection and cloud schemes, resulting in underestimating both the upwelling long-wave flux and absorption by thin cirrus clouds near the tropopause.

As mentioned previously, CCSM2 high-latitude and polar surface temperatures are higher than both CSM1 and observations, by 5° to 10°C, for both land and sea ice in the polar and subpolar regions, particularly in winter months. Low-level winter temperature inversions are present as observed but with elevated temperatures. The height of the inversion is around 1 km, only slightly lower than observed.

CCSM2 produces excessive low-level winter cloud cover, over 80% coverage, rather than the 20 to 30% observed. Such low-level cloud reduces surface long-wave cooling and leads to higher near-surface temperatures. Higher surface temperatures could also be due to excessive atmospheric heat transport.

Improvement in the simulation of winter low-level cloudiness is likely to lead to better low-level temperature simulation in CCSM. (It must be noted that a reduction in effective cloud cover by optically thinning low-level clouds will produce the desired effect, even if the actual cloud cover remains high.) Removal of the remaining temperature biases may require improved transport, surface flux, and boundary layer schemes.

Recently, simple representations of missing microphysical processes have been tested in CAM2. These are introducing the latent heat of fusion in both stable and convective processes, exporting liquid and ice from convection to stratiform clouds, separating the stratiform liquid and ice variables and transporting both species, and allowing ice crystals to sediment within stratiform clouds. Initial results suggest that these improvements not only warm the tropical tropopause but also tend to reduce the winter warm bias at high latitudes over land.

During summer months, the surface energy balance also involves short-wave heating and stronger surface cooling due to latent heat. Over sea ice, temperatures are controlled by melt processes. Over land, cloud cover and optical properties (i.e., cloud condensate and particle size) strongly influence surface short-wave heating and therefore surface temperatures. There is evidence of a lack of low-level clouds over summer polar land surfaces, which could lead to a small warm bias. Over sea ice, a deficit of downward short-wave radiation at the surface is likely due to excessive amounts of cloud condensate. The surface temperature biases for polar land and sea ice in CCSM2 may also derive from deficiencies in the land and sea ice physics.

Plausible changes to fractional snow cover formulation in the land model also appear to reduce some of the warm winter temperature bias in the Northern Hemisphere. The current parameterization of fractional snow cover results in a low fraction of the grid cell being covered by snow, even for deep snow. An improved parameterization results in greater coverage of snow in a grid cell, giving high land surface albedos and lower temperatures. For the sea ice model, uncoupled simulations with CAM2, where SST, sea ice thickness, and area are specified, still produce a warm bias in the high northern latitudes. In fully coupled simulations with CCSM2, sea ice in the arctic is biased thin and the areal extent is too low. Positive feedbacks associated with the albedo of sea ice and its insulating properties exacerbate the warm surface bias, approximately doubling the bias compared to uncoupled simulations in the vicinity of the Arctic Ocean.

b. Identifying the Physical Basis for Low and High Climate Sensitivity

The scientists involved in developing atmospheric general circulation models (AGCMs) at GFDL and NCAR have begun a collaboration to understand and compare aspects of their models and their simulated climates. Preliminary results suggest that the two models have very different climate sensitivities to increased forcing by anthropogenic greenhouse gases. When carbon dioxide is doubled over present-day values in the CAM2 coupled to a slab ocean model, the global mean surface temperature increases by about 2 K. When recent versions of the GFDL atmospheric model, AM2, are subjected to the same forcing, the global mean temperature increases by approximately 4 K. In their current configurations, the GFDL model is therefore about twice as sensitive as CAM2. This difference is the subject of active investigation and will motivate a number of experiments in the near future. It is possible that the differences are driven mainly by differences in the schemes used to predict cloud amount and cloud properties used by the two models. Both groups have begun analyzing the variations in cloud distributions that occur during ENSO cycles. These studies are based upon Earth's satellite radiation data and satellite retrievals of cloud properties from 1980 to present, spanning four major episodes of warming in the eastern Pacific. Surface observations of clouds and field observations will also be integrated into the analysis. Preliminary results indicate that both models exhibit systematic biases, although the effects of the biases are opposite in sign.

One method for quantifying the role of various processes in climate sensitivity is to subject both models to identical changes in surface temperature. This method mimics the changes in surface temperature obtained in long transient forcing experiments, but the experiments can be shortened considerably and analyzed more readily. The forcing is not prescribed; instead, the temperature change is imposed and the forcing corresponding to that change is computed by the atmospheric models. GFDL and NCAR have already undertaken "Cess"-style experiments with prescribed globally uniform increments in surface temperature. Both groups have developed offline tools for decomposing the radiative forcing into contributions from changes in atmospheric moisture, thermal structure, cloud amount and cloud properties, and surface albedo. Preliminary analysis suggests that changes in temperature and humidity contribute to the forcing in very similar ways in both model systems, but the contributions from clouds are quite different.

It is also possible to impose the regionally varying temperature anomalies derived from fully coupled simulations of climate with doubled CO_2. This type of experiment retains the advantages of the "Cess" approach while incorporating realistic meridional gradients in the temperature anomalies. The responses of the models to these global warming scenarios will be examined for significant regional differences that could be linked to differences in model physics.

A final class of experiments will simulate Earth's system under paleoclimate regimes. These regimes feature significant changes in surface temperature associated with large variations in greenhouse gases and solar forcing. GFDL and NCAR will coordinate mixed-layer simulations of the last glacial maximum.

c. Identifying the Physical Basis for the High Polar Amplification in the Coupled Model

Positive feedback mechanisms amplify climate variability and climate change in the arctic. Ice albedo feedbacks associated with variations in snow and sea ice coverage have been shown to be a key factor (e.g., Manabe and Stouffer, 1980). In addition, variations in the thickness of sea ice tend to reinforce surface atmospheric temperature anomalies by altering the heat and moisture transfer from the ocean to the atmosphere. While there is agreement among models that the arctic warms more than the subpolar regions do when subject to increasing levels of greenhouse gases in the atmosphere, the range of warming projections in the arctic is larger than elsewhere on Earth (IPCC, 2001).

Holland and Bitz (2003) determined that climate sensitivity of the Northern Hemisphere as simulated by CCSM2 is among the highest in all of the models taking part in CMIP, although the overall climate sensitivity in CCSM2 is lower than most. These results suggest that feedbacks in the arctic may be responsible for an even greater portion of the total global temperature change in CCSM2 than has been previously recognized. Additionally, this study indicated that the magnitude of polar amplification was related to sea ice conditions in the control (present-day) climate. In particular, the location of maximum warming at high northern latitudes was related to the control climate ice extent, and models that simulated thinner sea ice generally had higher polar amplification signals at doubled CO_2 conditions.

The PCWG plans to further investigate the high CCSM polar amplification by first evaluating the influence of sea ice on the simulated climate sensitivity. A model with no feedbacks related to sea ice has been constructed to explicitly identify the local and global climatic response to sea ice feedbacks in CCSM2. To do this, the model will be integrated under a radiatively forced scenario (e.g., increasing CO_2) with the sea ice fixed based on a climatology from a present-day simulation. The "data" sea ice model has already been altered to read in a climatological mean annual cycle constructed from the control CCSM2 integration and has successfully run for several decades. A simulation with a transient increase in CO_2 is under way. Comparing this simulation to present-day and radiatively forced simulations with a fully active sea ice model gives a direct measure of how sea ice feedbacks influence the global and geographical response to radiative forcing. This experiment will provide a measure of ice-albedo feedback in combination with other sea ice-related feedbacks, such as those due to surface evaporation and ocean-atmosphere heat exchange. Our assessment will give an unbiased estimate of the feedback strength due to sea ice that is directly comparable to estimates of other climate feedbacks. This will lead to an improved understanding of the role that changes in sea ice conditions and associated feedbacks play in the relatively high polar amplification signal seen in the CCSM2.

Additional studies are planned to examine the influence of various sea ice model parameterizations on the high polar amplification in CCSM2. CCSM2 has a relatively sophisticated sea ice model with a number of parameterizations that may influence the simulated climate feedbacks. For example, the model includes a subgrid-scale ice thickness distribution (Bitz et al., 2001; Lipscomb, 2001) to account for the high spatial variability present in the observed sea ice. It is anticipated that this parameterization can modify high-latitude feedbacks. In particular, models that include an ice thickness distribution could well be more sensitive to climate change because they explicitly resolve thin ice, which more easily melts away, exposing the underlying ocean and reducing the albedo. Simulations will be run to test these hypotheses. Other sea ice parameterizations are also likely to affect the simulated polar amplification and will also be examined. These include parameterizations of the surface albedo, parameterizations of the sea ice thermodynamics, and parameterizations of ice-ocean-atmosphere exchange. Additionally, there is a plan to coordinate with investigators at GFDL and the Hadley Centre to "swap" sea ice model parameterizations and test their influence on simulated climate sensitivity. This will help identify differences in sea ice physics that lead to different polar amplification signals in these various models.

d. Diagnosis and Investigation of Variability

In addition to analyses of simulations performed with the fully coupled model, a number of uncoupled and intermediate coupled model simulations are planned in the near term to enhance the community's ability to study climate variability and identify biases in the CCSM2 component models.

An experimental protocol that has become the standard in the climate research community for evaluating AGCMs is one where the model is forced with the known global evolution of SST and sea ice concentrations. Such integrations form the basis of the Atmospheric Model Intercomparison Project (Gates et al., 1996, 1999), and therefore they are commonly referred to as AMIP experiments. These experiments allow detailed investigations of the time-varying behavior of the simulated atmosphere, including the detection of atmospheric climate signals related to variations in ocean surface conditions. AMIP-style experiments have been widely employed in studies of the atmospheric response to ENSO, the role of anomalous SST in drought and flood episodes, and decadal variability and trends of natural climate phenomena such as the PDO and the NAO.

While nearly all modeling groups have performed an AMIP ensemble with their AGCM, the typical size of the ensemble is 5 to 10 members, which is likely the *minimum* number necessary to reliably detect the climate signal related to the imposed lower boundary forcing (e.g., Kumar and Hoerling, 1995). In reality, determining subtle changes in the probability distributions of atmospheric variables arising from changed boundary conditions requires much larger ensembles, perhaps two to three times the typical ensemble size (e.g., Mehta et al., 2000; Sardeshmukh et al., 2000). Such arguments, of course, are likely to be model dependent, and the exact ensemble size also depends on the variable under consideration, time average, geographical location, and the season. Nevertheless, the CCSM program has made a useful contribution by providing the climate community with a 15-member ensemble of AMIP integrations with CAM2 for the period 1949 to present using the new SST and sea ice data set (Hurrell et al., 2003). In addition to monthly mean output, a large number of daily and subdaily fields will be saved, as requested by several users.

While AMIP simulations provide a benchmark, it could be argued that an equally important and perhaps even more desirable experiment is to include not only the observed variations in SST and sea ice but also changes in other external forcings (e.g., changes in greenhouse gas concentrations, aerosols, solar forcing). This would complement the Climate of the 20th Century integrations planned with CCSM2, which have been the usual approach in the climate modeling community. Indeed, one could argue that the most accurate simulation of recent climate change and variability would be given by an ensemble of AGCM simulations where all the observed forcing factors were included, the component of ocean surface temperature change caused by the changes in forcing was perfectly reproduced, and all remaining ocean surface changes were also perfectly reproduced. This data set would be more ideal than the simple AMIP integrations to compare to observed climate records, and it should provide a time history of atmospheric responses closer to observations than is likely with a coupled model. This approach has not been widely adopted, although it is not unprecedented (Folland et al., 1998). The CCSM program will make an important contribution to the broad research community through such runs. At the present, the CVWG plans to carry out 20th century runs using the next release of CAM2 in the summer of 2003.

Initially, a 10-member ensemble beginning in 1870 and run through the present will be provided, with an additional 10-member ensemble for the period since 1950 when the forcing data sets are more reliable. These runs will be valuable for examining the influences of both anthropogenic and oceanic forcing on recent climate change.

Experiments in which CAM2 is coupled to a grid of independent column ocean-ice models can be used to study several processes. These include local ocean-atmosphere-ice interactions, upper ocean processes such as the "reemergence mechanism" (Alexander et al., 1999), and atmospheric teleconnections between ocean basins. The latter includes the "atmospheric bridge" (Alexander et al., 2001) where changes in the air temperature, humidity, winds, and clouds associated with ENSO can generate ocean anomalies far from the equatorial Pacific. The ENSO-related SST anomalies that develop over the world's oceans can also feed back on the original atmospheric response to ENSO. Initially, two sets of AGCM experiments with different ocean configurations will be conducted to examine how air-sea interaction in various ocean basins influences the atmospheric bridge. In all of the experiments, SSTs are prescribed to evolve according to observations over the period 1950 to present in the tropical Pacific Ocean (15°S–15°N). The experiments differ in their treatment of the ocean outside of this region. In the "control" experiment, climatological SSTs, which repeat the same seasonal cycle each year, are specified at all remaining ocean grid points outside the tropical Pacific region. (This experimental design is often referred to as the "Pacific Ocean Global Atmosphere," or "POGA," in the literature.) In the mixed-layer model experiment, a grid of column ocean models is coupled to the atmosphere at each AGCM grid point over the ocean outside of the tropical Pacific region. Due to the absence of ocean currents and errors in the atmosphere and ocean model, surface heat and salt flux corrections are applied to maintain the observed mean seasonal cycle of the ocean model. Both experiments will consist of an ensemble of 10 simulations where the individual members are initiated from different atmospheric states obtained from a long CAM simulation.

The ocean component of CCSM2 will be coupled with the atmospheric mixed-layer model (AML) developed by Seager et al. (1995) as an intermediate step between the traditional ocean-only simulations and the fully coupled system. In ocean-only simulations, the surface heat fluxes are usually prescribed using standard air-sea transfer equations (Large and Pond, 1982; Large et al., 1997). This approach implies a relaxation of the model's SST toward the observed surface air temperature with a relatively short damping timescale (30 to 60 days for typical mixed-layer depths), so that the SST in the model can be expected to be strongly constrained by the surface forcing rather than by the interior ocean dynamics. The assumption implicit in common bulk formulations is that the surface air temperature is a given, as if the atmosphere had an infinite heat capacity. On the contrary, the atmospheric heat capacity is much smaller than the oceanic one, so that atmospheric temperatures can be expected to closely track SSTs. In the AML, surface air temperatures are computed from the model's SSTs and prescribed winds, so that SSTs can be more free to respond to changes in the ocean circulation, and the links between thermocline variability and SST variability are more reliable. The AML represents the well-mixed layer that underlies the cloudy portion of the marine boundary layer. It computes the air temperature and air humidity by balancing the surface fluxes, advection, atmospheric eddy transports, entrainment from above, and radiation. The AML has been successfully used in several climate applications (e.g., Seager et al., 2000, 2001). In eddy-resolving simulations, which may become feasible in the near future, the weaker constraint on SST when the AML is used can result in higher and more realistic eddy kinetic energy levels.

A series of simulations with the coupled POP-AML will be performed over the period 1958 to present. The ocean model will be dynamically forced with NCEP wind stress, while NCEP wind speeds and directions will be used for the AML. Cloud fraction and solar radiation will be derived from the International Satellite Cloud Climatology Program (ISCCP). Two simulations will be performed with the existing AML, while another two will be run with the AML modified to include the NCAR parameterization for bulk formulae.

VII. Scientific Questions Needing Major New Coupled Model Capabilities and New Resources

In previous sections, this Science Plan described a near-term program of investigation of present model properties with some development of model capabilities. In addition, a program of application of the present model technology to applied climate questions was put forward. The community has in mind many scientific questions about the climate system that require major new investment of scientific talent and computer resources. The questions and topics included in this section are not necessarily complete or exhaustive but rather representative of the scientific interests of the present CCSM community. They suggest priorities for the extension of the technical capabilities of the model over the next five years and provide an ambitious version of where the CCSM project can lead the way forward.

a. The Interaction of Aerosols and Climate

Aerosols affect the climate in a multitude of ways. They directly reflect and absorb solar radiation in the atmosphere, altering the vertical distribution of short-wave radiation available to the climate system. The amount of energy reflected or absorbed by aerosols depends on the physical and chemical properties of the particles. Aerosols also act as cloud condensation nuclei and regulate cloud properties, which strongly alter the short-wave and long-wave radiation budgets of Earth. Increased numbers of aerosol particles can increase the number of cloud condensation nuclei and in turn produce more of the smaller cloud droplets, which increases a cloud's optical depth. Production of these smaller cloud droplets also suppresses the growth of droplets into larger sizes that precipitate out of the cloud, thus leading to clouds with more condensate and/or longer lifetimes. Both of these changes lead to changes in the cloud's radiative effects on Earth's energy budget. Clouds also act as processors of atmospheric chemicals. Thus, changes in the amount of cloud condensate and/or cloud lifetime can affect chemical mechanisms, such as aqueous phase chemistry and gas phase photolytic reactions. Finally, removal via cloud precipitation is one of the most effective sinks for atmospheric aerosols. This process leads to the deposition of chemicals on Earth's surface, and these chemicals can be important to biogeochemical processes.

It is clear that aerosols provide an effective link among a number of components of Earth's climate system, where they connect the physical, chemical, and biogeochemical components of the system. The bridge across these various components is mainly through the hydrologic cycle. Given the multifaceted roles of aerosols in the climate system, it is imperative that the capability to model a fully interactive aerosol system be developed within the CCSM.

The goal of including a comprehensive aerosol model within the CCSM will be accomplished in stages. First, an offline chemical transport model that predicts aerosol mass concentrations for a number of species (sulfate, carbonaceous, black carbon, sea salt, and mineral dust) exists. This model has produced a realistic three-dimensional aerosol climatology that is now incorporated into CAM2. Studies by W. Collins (NCAR) and others indicate that this new aerosol climatology alters the vertical distribution of short-wave heating compared to the simple aerosol model used in previous versions of the atmospheric CCSM component.

Second, over the coming year, the aerosol prediction model will be migrated to the latest version of CAM2. This will allow for coupling between the atmospheric climate state and the aerosol system. Given the aerosol concentration and knowledge of the aerosol optical properties, the interaction of the direct radiative effects of aerosols on the climate system will be enabled. In addition to aerosols already in the model, an effort will be undertaken to include nitrogen-based aerosol species. Nitrate aerosols constitute roughly half of the chemical composition of observed aerosols in many locations, and they are a major source of nitrogen to the terrestrial biosphere. Also, the long-wave radiative effects of mineral dust aerosols are significant and will be included as a part of the existing aerosol model.

To accurately model the interaction of aerosols with clouds requires the prediction of aerosol number concentration. A concerted effort will be made to build an aerosol prediction scheme that allows for this capability. Presently, a number of numerical techniques exist to predict aerosol number. The CCSM community must entrain aerosol modelers into this activity over the coming years. Aerosol prediction schemes are computationally expensive and will require a significant enhancement to current computational resources if they are to be included in the standard version of the CCSM. These schemes will allow for a realistic interaction between aerosols and predicted cloud properties, thus constraining the indirect effect of aerosols for simulations of past, present, and future climates. Development of a comprehensive, fully interactive aerosol component to the CCSM is critical to the scientific goals of the CCSM and will need to be organized within one or more of the working groups.

b. The Interplay of Chemistry and Climate

Beyond the well-documented evolution of stratospheric ozone under the impact of chlorofluorocarbons (CFCs), the interplay of atmospheric chemistry and climate is becoming more recognized. Over the past 10 years, radiative forcings for a large number of greenhouse gases and certain aerosols have been evaluated for both the 20th and 21st centuries. Of all the greenhouse gases, tropospheric ozone causes the greatest uncertainty in radiative forcing. In particular, the forcing is very sensitive to the ozone vertical distribution. Chemistry is also important for the distribution and evolution of aerosols. Indeed, the distribution of aerosols is strongly influenced by the distribution of atmospheric oxidants, such as the hydroxyl radical and ozone. These oxidants are themselves dependent on the distribution of a large variety of chemical compounds emitted at the surface or directly in the atmosphere. Chemistry and climate are also directly linked through the formation of secondary organic aerosols. Emissions of chemical species can be strongly dependent on the climate. In particular, emissions of isoprene (an important biogenic ozone precursor) are very temperature dependent. Also, biomass burning in wildfires is a large contributor to the budget of nitrogen oxides, carbon monoxide, carbon dioxide, and ozone. These emissions will most likely dramatically change due to changes in temperature and precipitation patterns from climate change.

Because the chemical processes in the troposphere and stratosphere are highly nonlinear, it is crucial to have a realistic characterization of the chemical species and their reactions. Photolytic processes in the troposphere are strongly dependent on the column of ozone overhead. To fully comprehend the chemical couplings between the troposphere and the stratosphere, it is necessary to include a description of the chemistry for both regions. This requires the consideration of a large number of chemical species (typically 30 to 100) and their reactions. Inclusion of chemistry in the CCSM will necessitate a large number of modifications to fully represent the various feedbacks. In particular, interaction with the surface (land and ocean) is needed to represent exchanges (natural and anthropogenic emissions and dry deposition). Wet removal requires interaction with hydrological processes. As mentioned earlier, the chemistry will also influence and be influenced by the aerosol distribution. Finally, the explicitly calculated distribution of the chemical species then can be used to calculate heating rates and radiative forcings fully compatible with the modeled chemical state.

c. Abrupt Climate Change

The climate record shows evidence of rapid and extreme temperature change, sometimes in as little as a decade. An abrupt climate change is thought to occur when the climate system passes a threshold, so that a small perturbation can trigger a large response. Examples of threshold events include iceberg and floodwater outbursts in the North Atlantic that are seen in proxy data and are associated with the disintegration of the Laurentide ice sheet. The large input of fresh water may have in turn rapidly altered ocean circulation and influenced ocean heat transport. However, evidence for such outbursts preceding rapid climate changes remains uncertain. Furthermore, abrupt (albeit smaller) changes have been identified during interglacial times as well, so mechanisms in the absence of ice sheets must also be possible.

The mechanisms that cause abrupt changes are not fully understood, and there is general agreement that climate models do not properly represent them. The possibility that an abrupt change will occur in the future due to anthropogenic influences makes the need to better understand their mechanisms an essential element of projections of future climate. Climate models could be used both to identify mechanisms and to estimate their future impacts.

The following candidate processes are thought to be important for abrupt climate change and may require either refinements to existing parameterizations or additions to the model:

- deep water formation
- shelf processes
- fresh water runoff, storage/recycling, atmospheric moisture transport
- sea ice processes
- ice sheet processes
- atmospheric chemistry

d. The Role of the Middle Atmosphere in Climate

The impact of stratospheric variability on climate and the role of the middle atmosphere in climate change are currently open questions. There is increasing awareness that changes in the propagation characteristics of planetary waves in the stratosphere may play a role both in stratospheric climate, via dynamical and chemical interactions that affect ozone concentration, and in tropospheric climate by influencing such phenomena as the Arctic Oscillation. Several studies suggest that changes in the stratospheric circulation have a significant impact on the troposphere, altering planetary wave structures and storm track positions (Thompson et al., 2002). The dynamics of the stratosphere are 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." In order to understand the role of the stratosphere in climate variability, we must model and understand the coupled variability of dynamics and ozone in the stratosphere.

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 feedbacks 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 feedbacks between ozone and dynamics. This deficiency needs to be corrected.

Several studies have hypothesized that much of the climate variability over the last several centuries is correlated with variations in solar irradiance. There has also been considerable discussion of the observed correlation between the 11-year solar cycle and tropospheric temperature and geopotential patterns. However, the total solar irradiance variations do not appear to be large enough to force the observed climate variability in existing models. Satellite observations of solar irradiance over the last 20 years show that the variability is largest in the extreme ultraviolet (wavelengths shorter than 200 nm), although most of the variation in total irradiance is at longer wavelengths. The radiative transfer codes in current climate models generally do not include wavelengths shorter than 200 nm, because these wavelengths are almost entirely absorbed in the thermosphere and mesosphere and do not penetrate into the vertical domain resolved by climate models. The effects of solar irradiance variations on the troposphere and surface climate may come indirectly, through changes in the stratospheric ozone distribution and circulation. In order to understand the natural variability of the climate system, it is of considerable importance to determine whether variations in solar irradiance can play a significant role. Addressing this question will require models extending vertically through the mesosphere and including interactions between ultraviolet radiation, ozone chemistry, and dynamics (Thompson and Solomon, 2002).

Research investigating the climate effects of the middle atmosphere and the effects of solar variability at small wavelengths requires a model system that extends from the surface through the mesosphere, including interactive ozone chemistry. These requirements are expressed in the plans for the Whole Atmosphere Community Climate Model (WACCM) project. The development of WACCM is motivated by an appreciation of the importance of coupling between different atmospheric regions, and the necessity of studying dynamical and chemical processes in an interactive and comprehensive framework. From a practical point of view, it is sensible to build the WACCM framework upon the CCSM project thereby benefiting from the developments of the atmospheric component of CCSM, as well as the diagnostic infrastructure that has been developed. On the other hand, there are specific needs that are crucial for successful coupling of the troposphere with the stratosphere and mesosphere. One example of the requirements has been discussed in Section VI in terms of the (too) cold tropical tropopause.

e. Climates of Extreme Warmth of the Past 100 Million Years

For much of its history, Earth's climate has been warmer than it is today, with estimates of global mean surface temperature as much as 4°C to 8°C higher. Based upon geologic evidence of many forms, including fossil plants and animals, geochemical data, and evidence of sea level variation, Zachos et al. (2001) estimate that Earth was completely or nearly ice free for more than half of the time in the past billion years. Of particular note are the extremely warm climates of the middle to late Cretaceous (90 to 100 million years ago, or Ma) and the late Paleocene through early Eocene (60 to 50 Ma) (Crowley and Zachos, 2000).

The climates of extreme warmth of the past 100 million years, while showing different characteristics (especially in terms of typical life forms), exhibit very similar surface temperature gradients. Most representative of these climates are tropical temperatures similar to or slightly warmer than present-day values, and high-latitude temperatures that are much warmer than their present-day counterparts. This results in a distinct and characteristic pole-to-pole surface temperature gradient that is much weaker than what is observed today and during other nongreenhouse climates (Crowley and Zachos, 2000). Also characteristic of these climates are continental interior temperatures at midlatitudes that were very much milder than occur in the present day (e.g., Sloan and Barron, 1990; Sloan, 1994; Greenwood and Wing, 1995). While the changing positions of the continents and oceans may play some role in the climate of these time periods, modeling to date has suggested that the distribution of land and ocean is a very minor factor in explaining climates of extreme warmth (e.g., Barron and Washington, 1984).

With this in mind, studies that seek to explain the evolution and stability of these past warm climates have focused upon the roles of various greenhouse gases (Barron et al., 1993; Sloan and Rea, 1995; Shellito et al., 2003), clouds (Sloan and Pollard, 1998), ocean dynamics (Huber and Sloan, 2001; Otto-Bliesner et al., 2002), waterways, and the biosphere (Otto-Bliesner and Upchurch, 1997; DeConto et al., 2000; Sewall et al., 2000) in explaining these climates. These modeling studies have greatly increased our understanding of the role of ocean dynamics in explaining evidence of deep ocean warmth (Otto-Bliesner et al., 2002). However, modeling studies to date have not been able to reproduce adequately the land surface temperature characteristics described by the geologic evidence.

In order for the paleoclimate modeling community to continue to explore and make progress in the understanding and explanation of the evolution and causes of past warm climates, the following capabilities will be needed:

- to carry out very long (1000-year) integrations at a reasonable computational cost
- to spin up a fully coupled modeling system at a modest computational cost (note that this is a significant challenge for physical conditions largely different from present)
- to carry out ocean integrations without needing to specify the surface oceanic heat flux
- to complete atmospheric chemistry realizations for constituents including methane and stratospheric water vapor
- to more realistically represent biogeochemistry that is established for issues related to paleoclimates (again, this may be different from present-day realizations and parameterizations)
- to use a land surface model (including river routing and dynamic vegetation) that takes advantage of new modeling improvements, but at the same time allows for the limited knowledge about such conditions and the coarser spatial resolutions that exist in paleoclimate modeling studies.

f. High-Resolution Ocean Effects on Climate

A central question in oceanography is what role mesoscale ocean processes play in establishing the mean climate, its variability, and the response to climate forcing. The majority of the kinetic energy of motions in the ocean exists at scales substantially smaller than are resolved by current versions of the CCSM2 ocean component model. These motions include both the time varying mesoscale ocean eddies and many dominant features of the time mean general circulation: western boundary currents, eastern boundary upwelling zones, frontal features of the ACC, etc.

While parameterizations of the effect of mesoscale eddies on the distribution of scalar properties have advanced considerably in the last decade (Gent et al., 1995), they still are rudimentary. Physical processes that are not currently represented by mesoscale eddy parameterizations include the interaction of eddies with the mixed layer through broadening of the resonance and an imparted parity bias in the dispersion of inertial waves (Klein and Treguier, 1993), the generation of recirculation gyres adjacent to western boundary currents (Jayne and Hogg, 1999), and the interaction of eddies with bottom topography (Adcock and Marshall, 2000). Further, current eddy parameterizations are all local in nature, that is, they associate mixing with local gradients of the density and flow fields. There are substantial basin scales and interbasin transports associated with long-range propagation of coherent eddies, such as Agulhas rings and "meddies," that cannot be represented with this class of parameterizations. Vertical motion in mesoscale eddies has also been shown to substantially modify primary productivity of oligotrophic marine ecosystems (McGillicuddy et al., 1998). Parameterizations that depict eddies as a mixing process cannot represent this nutrient transport mechanism.

The small scales of boundary current systems have important implications for climate change and climate sensitivity, as well as for the time mean circulation. For example, the export of fresh water and sea ice from the arctic through the subpolar North Atlantic occurs almost exclusively in the narrow boundary current system along the Greenland and Labrador coasts. This serves to isolate the stabilizing effect of low surface salinity from the convective regions further offshore that drive the thermohaline circulation. This segregation of water masses has important impacts on the stability of the thermohaline circulation in climate change scenarios.

In order to improve our understanding of ocean mesoscale processes in the global climate system, and to make progress toward refining existing and developing new eddy parameterizations, we need to develop a version of the CCSM that explicitly resolves these oceanic scales. A suite of simulations in ocean-alone, coupled ocean-ice, and fully coupled mode is needed to investigate the range of scientific questions outlined above.

Recent simulations with basin-scale ocean models suggest that a horizontal resolution of 10 km or less is necessary to adequately simulate both the intense western boundary current systems and the mesoscale eddies. It appears that the formulation of the hydrostatic primitive equations used in the CCSM2 ocean component model should be adequate for resolutions of at least 5 km. The model development that is required to accomplish simulations in this resolution regime fall into two categories: subgrid-scale parameterization and performance portability.

Beyond a simple increase of resolution of the present model, we will need to continue to explore the sensitivity of eddy-resolving solutions to subgrid-scale parameterizations. As mentioned above, significant interaction between mesoscale eddies and diapycnal processes (interior and boundary layer) is expected. This will, in all likelihood, require tuning and further development of the diapycnal mixing schemes currently used in the CCSM2 ocean component. Despite the fact that mesoscale eddies will be explicitly resolved, it appears that adiabatic closure schemes will still be required (Roberts and Marshall, 1998). Recently, an adiabatic closure scheme appropriate for use in both eddy-resolving and non-eddy-resolving models has been developed and implemented in the POP model. This scheme is a horizontally anisotropic generalization of the Gent-McWilliams parameterization. It has been tested in a preliminary 1/10° simulation of the North Atlantic Ocean with promising results. It permits realistic eddy energies, as well as improving some aspects of the mean circulation when compared to simulations using the more standard (nonadiabatic) horizontal tracer diffusion operator, and it results in stronger meridional heat transport and overturning circulation. Further testing and tuning of this and other subgrid-scale parameterizations in eddy-resolving models is a high priority and will require significant computational resources.

The increase in resolution in going from a grid size of 100 km to 10 km results in an increase in computational cost by a factor of approximately 1000 over the current CCSM2 ocean component and will require access to the highest performance computational systems available. The current version of the ocean component of CCSM2 is performance tuned to parallel scalar architectures. In order to exploit systems such as the Japanese Earth Simulator, which might support this type of computation in the near term, performance portability to vector-based systems must be achieved. Further, it is clear that the implementation of this research strategy will require significant collaboration with groups outside NCAR, both to secure the computational resources necessary to carry out the simulations and to thoroughly analyze the results. Collaborative arrangements are already in place between the OMWG and LANL, the Naval Postgraduate School, and the Central Research Institute of Electric Power Industry (CRIEPI) to carry out global eddy-resolving ocean simulations with the same base code and compatible model configurations. Up to this point, virtually all of the eddy-resolving simulations undertaken by this collaborative group have been carried out on systems outside NCAR. In order for the CCSM to meaningfully participate in this effort, and particularly to guide coupled integrations in this resolution regime, capability-mode computational resources at NCAR must be secured to carry out some of these simulations. In order to facilitate analysis of the results of the simulations, the infrastructure (software and hardware) necessary to manipulate (not just store) multiterabyte data sets will need to be developed. Our experience with running basin-scale eddy-resolving simulations indicates that the observational oceanographic community will have a strong interest in using results of these simulations in a wide variety of studies. In order to serve this community, we must be prepared to subsample and perform some processing of results.

g. The Role of Coastal Interactions in Large-Scale Climate

Distinctive physical features of the land-sea margin, including wind alignment and shear, oceanic surface temperature, and oceanic stratus and orographic cumulus cloud regimes, have important large-scale climate impacts, but they are poorly resolved in present global climate simulations. These effects are particularly significant in tropical, subtropical, and ocean eastern-boundary upwelling regions but may be important in other regions as well. Distinctive biological features of the land-sea margin, including high primary productivity, river/wetland influences, and rapid biogeochemical cycling, have important large-scale impacts on the distributions of the chemical components of the atmosphere and ocean, hence on climate. Again the upwelling regions are conspicuous. Regional climate, ecosystem functioning, and land-surface exchanges in general have significant variance on scales smaller than are well resolved in present global climate simulations. Thus, to assess the regional consequences of global climate change, a means of simulating the downscale influences is necessary, and it is equally important to systematically investigate the possibly important feedbacks onto the large-scale climate from these active interaction zones.

CCSM2 and other coupled climate models generate very warm (> 5°C) SST biases along the west coasts of South America, South Africa, and California. These regions are physically similar in their steep near-coast orography, an equatorward coastal winds regime that favors upwelling, and persistent nonprecipitating stratus clouds. These characteristics suggest a common cause for the biases. Furthermore, numerical experiments are suggesting that these biases appear to be a cause of, rather than a response to, long-standing coupled model deficiencies in the simulation of the ITCZs. Specifically, when near-coastal ocean temperatures of an otherwise global coupled model are forced to remain close to observations, there is a marked improvement in the ITCZ structures in both hemispheres in the Atlantic and Pacific regions. Most welcome are the formation of a distinct northern ITCZ in the Atlantic and a contraction of the spurious double ITCZ across the central and eastern South Pacific.

Coastal meteorology appears to be a major contributor to the SST biases. Specifying observed solar radiation and winds in the coastal region removes most of the SST bias along the Pacific coast of South America and about half of it off the Atlantic coast of southern Africa. The remaining bias is likely due to ocean circulation (e.g., upwelling), because ocean processes have been shown to be responsible for much of the low-frequency SST variability in these regions.

Continental margins occur at the triple intersection of land, ocean, and atmosphere and are strongly affected by sediment, organic, and nutrient loadings from land and by exchange with the open ocean. The tight coupling between the water column and shelf sediments in turn influences processes such as nutrient upwelling, denitrification, and trace element cycling, with potentially far-reaching effects on global biogeochemical cycling as a whole. Sequestration of organic and inorganic matter is higher in continental margins than in the open ocean, and estimates of the land-ocean flux of carbon are of the same order of magnitude as oceanic uptake of anthropogenic CO_2. However, even though about half of the global estimate of new production occurs over continental shelves and slopes, it remains unclear whether these regions are strong sinks for CO_2. The few surveys of air-sea CO_2 fluxes on continental margins indicate that some coastal margins act as CO_2 sinks (e.g., South China Sea) and others as CO_2 sources (e.g., coral reef environments). Quantifying the role of the coastal zone in the global carbon cycle is difficult because it is a temporally and spatially heterogeneous system that is not well characterized by steady state processes.

Coastal ecosystems and their biogeochemical processes vary across scales dictated by geography, bathymetry, and processes such as tides, upwelling, and hydrological inputs.

The fate of terrigenous sediments, carbon, and nutrients deposited to the coastal zone is not well quantified, and how much they are affected by both physical and biological processes or by exchange with the open ocean is poorly understood. In addition, terrigenous and marine biogeochemical fluxes are likely to change in response to climate change and to human activities both on land and directly within the coastal zone.

Coastal regions exhibit substantial fine-scale variance on scales of 10 to 100 km, as is quite evident in satellite images of stratus clouds, SST, and ocean color. To investigate their possible importance in climate, with present computing power, requires an embedded regional submodel, at least for the ocean if not also for the atmosphere and land surface. Present opinion is that the eastern boundaries of oceans in the tropics and subtropics are likely the coastal zones of greatest climatic and biogeochemical importance. Tropical and subtropical coastal dynamics may be an important component in the simulation of the ITCZ and other aspects of ocean-atmosphere coupling. Therefore, a relevant, although not necessarily unique, model configuration would be to embed a coastal strip 300 km wide between appropriate latitudes along the eastern boundaries of Africa and the Americas with a horizontal resolution of 5 km to simulate their climatic influences. In a more ambitious research program, regional models could be embedded within the global CCSM models to investigate climate downscaling and upscaling interactions broadly across many geographical regimes.

During the past several years, scientists at Rutgers University and University of California, Los Angeles (UCLA), have systematically been developing the capabilities of the Regional Oceanic Modeling System, ROMS (Shchepetkin and McWilliams, 1998, 2003a, 2003b; Haidvogel et al., 2000; Marchesiello et al., 2001; Penven et al., 2003) and applying those capabilities to a variety of regional modeling problems. ROMS is a combined physical circulation, plankton ecosystem, biogeochemical cycle, sediment, and river inflow model. As such, it is an appropriate tool for CCSM to investigate regional boundary coupling. Its simplest implementation would be to receive basin-scale boundary and surface forcing data from the global CCSM models in order to calculate the regional response and feed it back as altered atmospheric fluxes over the subdomain region. In a more sophisticated implementation, ROMS could be embedded within the global models and be fully interactive through the fluxes across its lateral and surface boundaries.

Downscaling of coarse-resolution atmospheric fields to provide statistical distributions of subgrid temperature, precipitation, radiation, humidity, and wind speed over land will be an important area of research in the coming five years. As the coupled model begins to incorporate increasingly sophisticated treatments of the terrestrial carbon and other biogeochemical cycles, these subgrid-scale representations will become critical to accurate predictions of net biogeochemical exchanges between the land and atmosphere, particularly in regions of complex terrain and in regions of strong horizontal surface climate gradients, such as coastal zones and the inland transitions from coastal to continental climate regimes. Conservation of mass and energy will be critical issues, as will the appropriate subgrid characterizations of the land area. The recent modifications to data structures and subgrid representations in CLM (version 2.1) provide a good foundation for tackling these problems. CGD researchers are also developing high-resolution surface weather databases (down to 1 km horizontal resolution for some regions) that will be useful in developing and testing downscaling schemes. Close collaboration with CAM developers will be required to resolve conservation issues.

As the description of biogeochemical processes on land and in the oceans becomes more sophisticated, it will become necessary and possible to improve the coupling between the model components through interactions in the coastal zone. From the land, the critical elements to put in place are fluxes of biogeochemical species from the plant litter and soil into streams; the transport and transformation of these species through the river continuum; a representation of sediment transport, dams, and diversions; and an interface to pass control of the biogeochemical processes to the ocean model in or near the estuary zone. In-stream transport and transformations are a central aspect of this connection that has received little or no attention in the CCSM framework. Proper treatment must include the variance in dominant mechanisms with stream order, from allochthonous processes in the low-order streams (dominance of inputs from the land surface) to autochthonous processes in higher-order streams (dominance of internal recycling, including multiple exchange cycles with transported sediment). This work will require new collaborations with the terrestrial aquatic biogeochemistry community.

h. Matching High-Resolution Results with the Needs of Assessment

An increasingly important application of climate system modeling is the production of data sets for use in assessing the consequences of potential climate changes. While some integrated assessment paradigms are able to link changes in global or zonal mean quantities to effects or damages through aggregated models, most assessments of consequences require spatially disaggregated information. In addition to assessment of potential impacts and damages, models can also be used to evaluate mitigation and adaptation measures, and as a more solution-oriented approach to climate change gains momentum, estimation of the efficacy of these measures will increase in importance. Requirements of impact, damage, mitigation, and solution studies have several common features, linked to the need to relate climate processes to human concerns. These requirements relate to regional credibility, resolution of relevant scales, and production of required climate system variables. A fourth topic, discussed briefly, is the link between global models and regional climate models and specific needs arising from this methodology. These requirements are discussed one by one below.

Regional credibility. Currently, climate model projections of global mean quantities and perhaps zonal patterns have more credibility than do projections of regional changes. Small-scale climate processes not well resolved in models affect regional climates. Some regional processes are not simulated well just because of model resolution, such as effects of land surface variability or ocean eddies. Other processes are not captured because of the parameterizations used or numerical methods. An example is the occurrence of spurious oscillatory patterns downwind of major mountain ranges. Some regional failures result from the interaction of model resolution and parameterizations, such as interactions between scale, clouds, and convection that vary between physics packages and scale in a complex fashion.

In order to simulate regional climates effectively, key drivers must be correct. These include correct routing of major ocean currents, simulation of storm track location, and seasonal processes such as snow cover. Major regional features of the climate system must also be correct, including phenomena like the monsoon, modes such as ENSO, and global patterns like the ITCZ. Regional variability requires that the major modes such as ENSO, NAO, and PDO be captured. The above requirements for the mean and variable features of the climate system are, in a sense, scale independent in that they are required for regional climates at any degree of resolution. In principle, the geography and variability of regional climate can be captured at a wide range of model resolutions, although in practice, some patterns are most easily captured by increasing model resolution.

The need for credible regional climate information—independent of the scale of the simulation—is, first, to simulate the major modes and patterns that control regional climates. This is a first-order requirement for the model to be useful in climate science. However, if regional spatial patterns and spatial-temporal modes are not reasonable, then higher-resolution simulation is not useful. Second, the processes causing simulated regional phenomena such as ENSO or the monsoon must be documented and must plausibly resemble the mechanisms thought to operate in nature. Third, regional statistics, including mean, variance, and other characteristics, must be available and documented. Fourth, a significant fraction of regional variability arises from modes of the climate system—modes that may change with climate change. Since these modes have limited predictability, large ensembles are needed to characterize variability and extremes probabilistically at the regional scale. It is possible or even likely that larger ensembles are needed to generate useful statistics for regional scales than are required for global studies. If high uncertainty remains about regional climates despite the best efforts to improve simulations, then large ensembles and multimodel ensembles must be used to approximate the distributions of possible outcomes.

Scale resolution. Regional climates are characterized by a combination of regional-scale patterns, as discussed above, and local variability within regions. If the basic characteristics of regional climate and its variability are well simulated, then increased model resolution is helpful in understanding regional impacts. Topography is a key aspect of scale. In many areas, water managers are deeply concerned about water resources in a changing climate. Accurate projections of water resources depend on resolving a number of fine-scale issues. These include resolving orographic gradients in precipitation amount and rain vs. snow, localizing precipitation to the correct watershed, and resolving drivers of precipitation intensity that arise from frontal vs. convective processes and other factors.

Production of required variables. Since assessments and management are done at local scales, the higher the spatial and temporal resolution (in mean quantities and statistics), the more directly climate system model results relate to decision-making scales. This requires that the CCSM provide for increased spatial resolution, including drivers of smaller-scale variability, such as fine-scale orography and land surface contrasts, consistent with model skill, and archiving relevant variables and/or statistics as local studies often require daily or subdaily information (e.g., for precipitation intensity). It follows from the discussion above that changes in mean quantities and higher moments of distributions are important in applied climate science. Changes in extremes, changes in the shape of distributions of climate variables, and changes in intensity can have major impacts on hydrological, living, and built systems and are required for assessment, "what if," and solution-oriented studies. Several levels of statistical information are needed from the CCSM. First, for each model run, statistics characterizing time and space scales not directly resolved in history files should be archived. These capture variables like precipitation intensity and high temperature exceedances. Second, statistics over ensembles are needed at resolved and unresolved scales in order to characterize the probability and predictability of the phenomena in question. Finally, statistics of all variables over multiple scenarios are required as well in order to link results to the assumptions in the forcings employed.

Regional climate models are increasingly used in "downscaling" large-scale changes to even finer resolution than can be simulated in the parent climate model. While there are conceptual and technical problems with this approach, it has proved useful in understanding systematic effects of orography, land-ocean contrast, and land surface characteristics. It remains a useful tool in bringing climate change results closer to hydrological, ecological, and decision-making scales. The use of regional climate models generates several requirements for CCSM and embedded regional climate model (RCM) simulations. The initial and boundary condition variables must be saved at the highest possible time and space resolutions to be used in forcing the regional climate model. The full suite of climate and surface variables needed by RCMs must be saved. When embedded RCMs are used, the finer-scale orography and land surface properties should, when aggregated to CCSM resolution, be consistent between model resolutions. Most topographic and land surface data sets are built from high resolution data sets, and when such data sets are built for the CCSM, higher resolution products should be archived for use both in future, higher-resolution CCSM runs and by RCMs.

Resources for assessment and solution-oriented runs will be significant, but many of the required runs are needed for multiple purposes. Many of the needs described above will be met by experiments proposed in the section on applied climate modeling (V.a). This area of work is "user-driven," and the CCSM experiments will need to be responsive to the requirements arising from the community. There has been input from the community on variables to be saved, needs of RCMs, and some other aspects of the problem. However, the complete suite of needs has not been articulated, and of course, it will change over time. Continued input from the CCWG and other organized activities will be used to steer the assessment, solution, and high-resolution experiments.

i. Delineation of Sources of Climate Variability

Processes in the upper atmosphere (stratosphere and above) likely impact the broader climate system in a number of ways. For example, solar variability could influence the troposphere through changes in the middle and upper atmosphere, and anthropogenic forcing could alter the chemical composition of the stratosphere, which in turn could feed back on the dynamics and thermodynamics of the troposphere. The natural variability during winter in the stratosphere could influence tropospheric climate patterns such as the NAO. To explore these and other upper atmosphere climate system interactions would require high vertical resolution in the upper atmosphere. One possibility would be to use WACCM in place of CAM in some CCSM studies.

While the current version of the CCSM simulates some aspects of ENSO well, there is still room for a great deal of improvement, i.e., the warming associated with ENSO extends too far west, the period of variability is more biennial than observed, and the amplitude is somewhat weaker than observed. Likewise, there are serious deficiencies in the simulation of tropical Atlantic variability. Since tropical SST anomalies influence the global atmosphere, obtaining realistic tropical variability is critical to the entire climate system. (See the discussion in Section VI for some near-term diagnostic studies and process-oriented model experiments aimed at exploring the causes of the biases in the tropical simulation.)

Clouds influence many aspects of the climate system, including the diurnal cycle, the Madden-Julian Oscillation, and the response to greenhouse gas forcing. The formation of individual clouds and cloud systems is a local phenomenon and occurs on short timescales. Thus, simulating realistic cloud properties may require high spatial and vertical resolution by embedding cloud-resolving models within CAM at some times and locations (e.g., "superparameterizations," Khairoutdinov and Randall, 2001).

The circulation in the Atlantic and Pacific Oceans includes a shallow meridional overturning cell that connects the tropics and subtropics. This overturning involves equatorial upwelling, poleward flow near the surface, subduction in the subtropics, and equatorward return flow in the upper thermocline. Variability of each of these processes may contribute to decadal variability and could influence the frequency and intensity of ENSO events. As a first step, detailed analyses of the subtropical cell could be performed in POP simulations forced by observations and in the CCSM2. Then adding passive tracers to POP could aid in tracking the pathways in the subtropical cells and other ocean circulations as well. The long CCSM simulations may be especially useful for investigating the causes of rapid climate change, with a focus on the role of the thermohaline circulation and variability in the tropical Pacific. A combination of present-day observations, paleoclimate data, and both the full-resolution and paleoclimate CCSM could be used to understand rapid change and its regional impacts.

With the relatively recent advent of global coverage of the oceans by satellites and the ocean profiling array, data are now available to validate models and better understand processes that occur in the southern oceans. For example, does the rate of deep water formation along the Antarctic continent influence the thermohaline circulation? Does the Antarctic Circumpolar Wave occur in the CCSM and, if so, are ocean dynamics critical to its existence? Using CCSM models in conjunction with observations and data from ocean data assimilation systems could help identify key sources of climate variability originating from the southern oceans.

As the atmosphere likely warms over the next century, it may be difficult to determine how feedbacks within the climate system influence the atmospheric warming. To address this question, the SST and sea ice conditions from CCSM scenario simulations could be used as boundary conditions in CAM with preindustrial or present-day CO_2 concentrations. Comparison of the CAM experiments with the original CCSM simulations would indicate how changing surface conditions influence the atmospheric temperature and circulation during global warming.

j. Climate Response to Solar Input on Long Timescales

Earth's climate responds to solar input variations operating on timescales from billions of years to millennia. Empirical correlations of climate records with solar activity proxy records and hypothesized solar irradiance variations suggest a causal relationship that needs to be rigorously tested with climate models such as the CCSM. Models of solar evolution indicate a solar luminosity increase of 20% to 30% for the past 4.7 Ga, arguing that the mean molecular weight of the sun has increased with the conversion of hydrogen to helium in the sun's core. The climates of early Earth and the contributing roles of solar irradiance, greenhouse gases, and continental positions are still inadequately understood. Examples include 3.5 to 4 Ga with evidence of free-flowing water (the "faint sun paradox"), low-latitude glaciation 750 and 600 Ma (the "snowball Earth"), and glaciation under high CO_2 levels at 440 Ma.

Milankovitch orbital variations of the solar input, seasonally and latitudinally, occur with periods of 400, 100, 41, 23, and 19 thousand years. Variations of the eccentricity of the Earth's orbit, obliquity (tilt) of Earth's axis, and precession of the equinoxes can be accurately calculated from celestial mechanics back 5 million years. This aspect of solar variability has been implicated as the primary factor over the last 400 thousand years for explaining the waxing and waning of continental ice sheets, the strengthening of the Asian-African monsoon and resulting higher lake levels, and the modulation of ENSO.

The response of the climate system to longer timescales of solar variability will be addressed with the CCSM. These simulations will evaluate the solar forcing alone and in concert with changes in greenhouse gases, aerosols, and land cover. It will be necessary to include ice sheet dynamics as an active component of CCSM. Simulations planned over the next five years at NCAR and in collaboration with our university colleagues include:

- last glacial maximum to present—forcing by Milankovitch solar variability with predictive carbon cycle, dust, vegetation, and ice sheets. Numerous examples in the proxy record show abrupt changes that will be investigated.
- last interglacial—example of extreme summer anomalies of solar input in the arctic forced by Milankovitch orbital variations. Proxy data suggests that the Greenland ice cap melted except for the summit. The time period will allow assessment of CCSM climate sensitivity for an end-member warm period with present-day geography.

k. Biogeochemistry and Ecosystem Dynamics

Investigating the complex, regional interactions of climate, ecosystems, biogeochemistry, and human society will require the development of complete coupled Earth system modeling capabilities (Doney and Schimel, 2001). The CCSM BGCWG has outlined a longer-term strategy involving a mix of enhancements to the ecological and biogeochemical sophistication of the present land and ocean models and expansion into aspects of the coupled system not currently considered within CCSM.

Current research suggests that, on balance, terrestrial ecosystems are at present a net sink for CO_2, but this conclusion masks considerable complexity and uncertainty with respect to future behavior. On centennial timescales, climate change may alter the large-scale distribution of natural biomes over the planet, with significant impacts on carbon storage. One recent model projection suggests widespread replacement of the Amazon rainforest with grasslands, tending to accelerate the atmospheric rise in CO_2 and other climate impacts (Cox et al., 2000). Human activities play a very direct, and often unaccounted-for, role in terrestrial ecosystem dynamics. Deforestation and other land use changes result in a CO_2 flux to the atmosphere, as high-carbon forests are turned into comparatively low-carbon pastures and croplands. This process is now occurring mainly in the tropics and is balanced to an unknown extent by regrowth on abandoned farm and pastureland. In the Northern Hemisphere, regrowth of forests on former farmland (especially in the eastern United States) and in previously harvested areas causes a sink during the rapid phase of young forest growth. Active land management in the western United States for fire suppression also appears to be contributing to carbon uptake. A major focus within the CCSM project will be the development of the modeling tools and validation data sets for incorporating and assessing historical and future land use; the dynamics of managed forest, rangeland, and agricultural systems; and deliberate carbon sequestration activities.

On an even longer timescale, pilot efforts should begin with integrating natural and social science research in respect to land use, as well as trace gas emissions. This is, perhaps, the only way to make credible predictions about the future of the climate and Earth's ecosystem given the pivotal role of human responses and decision making.

On the atmospheric chemistry side, three developmental paths are under way but will need to be augmented. First, prognostic dust emission, transport, and deposition are being included in the CCSM to study both the effects on atmospheric radiation and the impact on ocean biogeochemistry via the dust-iron fertilization linkage. Second, reactive chemistry is being incorporated into the model. Initially the focus will be on surface emission/deposition processes (e.g., volatile organic carbon, reactive N species), but the long-term objective is to incorporate a reduced set of reaction dynamics based on the Model of Ozone and Related Trace Species (MOZART) (Brasseur et al., 1998; Hauglustaine et al., 1998) chemistry model to look beyond carbon toward other important species, such as tropospheric ozone and methane. Third, nascent biogeochemical data assimilation capabilities are being developed for CO_2, carbon monoxide, and methane. The collection of atmospheric biogeochemical data over the last two decades by networks of surface stations and with time by aircraft and satellites provides critical, integrated information on the planet's biogeochemical cycles. Spatial patterns and seasonal to interannual temporal variations in atmospheric composition can be used to infer underlying mechanisms and regional sources and sinks. To fully exploit this record requires a combination of forward and inverse models. More emphasis is needed in CCSM to create the appropriate data assimilation tools for the atmosphere and extend biogeochemical assimilation into the land and ocean domains.

In the present CCSM, the land and ocean biogeochemistry are connected only indirectly via the physical climate, but the land and oceans also interact strongly through the outflow of nutrients and organic matter via rivers and groundwater. Many parts of the world are strongly impacted by coastal eutrophication (high nutrient loading) due to the runoff of excess agricultural fertilizers and sanitation waste, and the problem is expected to grow in the future. Eutrophication appears to be driving a large zone of anoxia near the mouth of the Mississippi in the Gulf of Mexico, and it has been linked, along with other direct human impacts, with the rise of harmful algal blooms and the decline of unique marine ecosystems such as coral reefs and eel grasses.

More broadly, as mentioned in Section VII.f., the coastal ocean and continental margins are not well resolved in the present CCSM framework. These regions support a substantial fraction of total marine primary production and fisheries and are the site for key biogeochemical cycling, such as much of the ocean organic matter burial, denitrification, and trace metal remobilization. Several new modeling activities will be needed within CCSM to close this land-ocean gap, including runoff of reactive biogeochemical species from the land surface model and downstream transport in rivers; treatment of the biogeochemical transformations that occurs in estuaries; high resolution model of coupled coastal ocean dynamics; and a dynamic marine sediment-water column module. The final component is also needed for millennial-scale and longer paleoclimate simulations, where calcium carbonate sediment compensation becomes important for damping large-scale changes in the ocean-atmosphere carbon system.

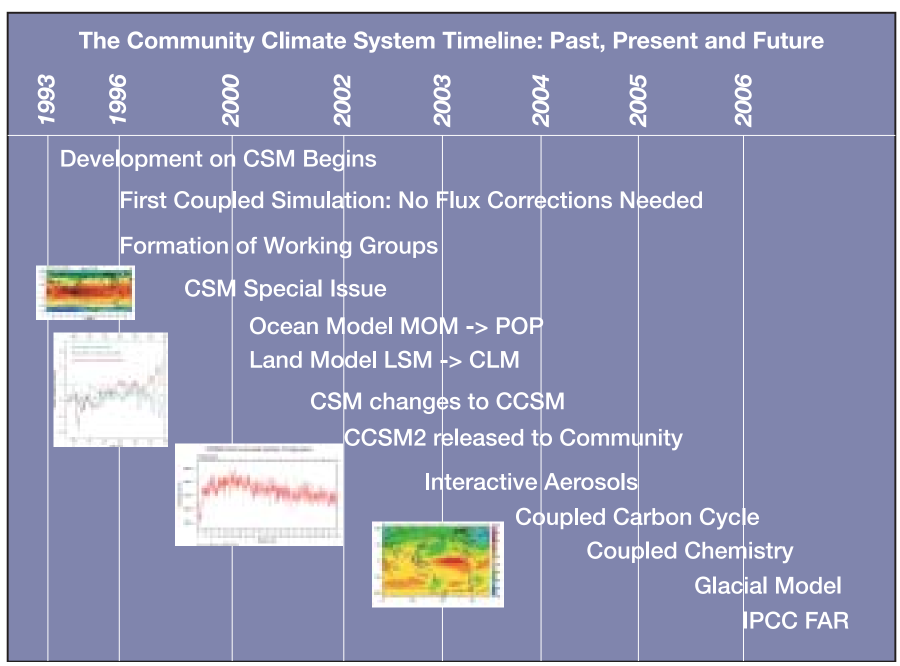
VIII. Products and Payoffs

The CCSM program as described above promises major advances in the scientific understanding of the climate system as a whole. It should also provide answers to many questions about the role of the individual components and should delineate circumstances where the individual components may be used with profit to better understand the physical mechanisms operating in Earth's climate system. In the near term, the major practical payoffs will come from the applied modeling component. There will be more detailed simulations of regional climate due to the improved representations of geography and topography afforded by the increased horizontal resolution of the simulations with CCSM2. There will be an increase in the understanding of the relative warmth of the 20th century as compared to earlier centuries based on the simulations of the variations in climate over the past millennium. Experiments will be performed with fully interactive aerosols so as to sharpen the estimates of the bounds of such effects in the climate evolution of the 20th century, as well as to sharpen the estimates of aerosol effects from energy use as distinct from those from agricultural practices. This will provide a more complete context for the analysis and interpretation of projections of future climate change resulting from human activities. Scenario runs will be undertaken to provide information for the consideration of policy options. There will be more confidence in the results of these experiments as considerable work will be completed measuring the uncertainty that is present in today's modeling systems through the use of ensembles. It is expected that there will be considerable progress on the provision of physical understanding for the large differences in climate sensitivity between various climate models and thus an ability to better estimate Earth's actual climate sensitivity.

In the near term, a major product of this effort will be the coupled model itself, running on a substantial number of different computer platforms and ready to be used by the community for research and applied climate modeling. In addition, the individual components of CCSM can be used by the community for research into the physical processes operating in the climate system.

Execution of the elements of this plan that build on the results achieved and look toward new or deeper scientific questions, such as better understanding of Earth's climate history and the coupling of chemistry, biogeochemistry, and the physical climate system, will place the CCSM program in the vanguard of large end climate modeling on an international level and will intellectually engage the climate community (Figure 17). It will also position the United States to avoid "climate surprises" in a rapidly evolving world and to be well equipped to address the climate policy questions that will arise in the future.

Figure 17. The timeline of the CCSM project.



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XI. Community Involvement and Outreach

a. Community Involvement and Outreach

The involvement of a broad community of scientists interested in climate simulations has been a high priority of the CCSM program 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 SSC, most with co-chairs from NCAR and one or more other institutions to foster collaboration.

CCSM Meetings	Date of Meeting	Venue of Meeting	No. of Participants
CMAP Scientific Advisory Council	2–3 March 1995		24
CMAP Scientific Advisory Council	7–8 December 1995	Boulder, CO	10
1st Annual CSM Workshop	15–17 May 1996	Breckenridge, CO	118
CSM Scientific Steering Committee	5 September 1996	Boulder, CO	10
Polar Climate Workshop	6–7 January 1997	Boulder, CO	
Atmosphere Model Working Group (WG)	14–15 January 1997	Boulder, CO	44
CMAP Scientific Advisory Council	21 January 1997	Boulder, CO	10
Joint CMAP Scientific Advisory Council & CSM Scientific Steering Committee	22–23 January 1997	Boulder, CO	18
Joint Seasonal-to-Interannual WG & Decadal-to-Centennial WG	7–8 May 1997	Boulder, CO	20
CSM Scientific Steering Committee	23 June 1997	Breckenridge, CO	13
2nd Annual CSM Workshop	24–26 June 1997	Breckenridge, CO	147
CSM Scientific Steering Committee	30 Sept–1 Oct 1997	Boulder, CO	10
CSM Scientific Steering Committee	27 January 1998	Boulder, CO	11
Paleoclimate Model WG	17–18 February 1998	Boulder, CO	30
Land Model WG	19–20 February 1998	Boulder, CO	26
Atmosphere Model WG	2–3 March 1998	Boulder, CO	33
Data Management Workshop	7 May 1998	Boulder, CO	22

CCSM Meetings	Date of Meeting	Venue of Meeting	No. of Participants
3rd Annual CSM Workshop	22–24 June 1998	Breckenridge, CO	174
CSM Scientific Steering Committee	22 June 1998	Breckenridge, CO	12
Joint CMAP Scientific Advisory Council, CSM Scientific Steering Committee, & CSM Working Group Co-Chairs	25 June 1998	Breckenridge, CO	25
CMAP Scientific Advisory Council	25 June 1998	Breckenridge, CO	12
Biogeochemistry WG	20 August 1998	Denver, CO	27
Joint Ocean Model WG, Polar Climate WG, & Paleoclimate WG	19–20 January 1999 19–20 January 1999 19–20 January 1999	Boulder, CO Boulder, CO Boulder, CO	24 14 16
CSM Scientific Steering Committee	10–11 February 1999	Boulder, CO	11
Joint Atmosphere Model WG, Natural Variability WG, & Seasonal-to-Interannual WG	12–14 April 1999 13–14 April 1999 13–14 April 1999	Boulder, CO Boulder, CO Boulder, CO	70
*CSM Advisory Board	29–30 April 1999	Washington, DC	37
4th Annual CSM Workshop	22–24 June 1999	Breckenridge, CO	205
Sea Ice Planning Meeting	27–28 September 1999	Boulder, CO	8
Land Model WG	8–9 November 1999	Center for Ocean-Land-Atmosphere Studies (COLA)	24
Software Engineering Meeting	10–11 November 1999	Boulder, CO	12
CSM Advisory Board	30 November 1999	Washington, DC	35
**CCSM Scientific Steering Committee	6–7 January 2000	Boulder, CO	13
Joint Ocean Model and Polar Climate WGs	18–19 January 2000	Boulder, CO	38
1st Data Processing and Visualization Workshop	31 Jan–4 Feb 2000	NCAR	13
Joint Seasonal-to-Interannual + Decadal-to-Centennial WGs	3–4 February 2000	COLA (Maryland)	35
Biogeochemistry WG	28–29 March 2000	NCAR	25
CCSM Scientific Steering Committee	12 May 2000	NCAR	10
CCSM Scientific Steering Committee	26 June 2000	Breckenridge, CO	12
5th Annual CCSM Workshop	27–29 June 2000	Breckenridge, CO	215
Joint Scientific Steering Committee/ CCSM Advisory Board and Working Group Co-chairs	30 June 2000	Breckenridge, CO	32
Software Engineering WG	2-3 October 2000	NCAR	20

*CSM Advisory Board changed its name from CMAP Scientific Advisory Council.

**CSM changed its name to CCSM (Community Climate System Model)

CCSM Meetings	Date of Meeting	Venue of Meeting	No. of Participants
CCSM Scientific Steering Committee	17-18 October 2000	NCAR	12
CCSM Coupler Meeting	25-26 October 2000	NCAR	10
2nd Data Processing and Visualization Workshop	13-16 November 2000	NCAR	8
Joint Atmosphere Model & Climate Variability WG	12-14 December 2000	NCAR	23
3rd Data Processing and Visualization Workshop	2-5 January 2001	UCLA	8
Atmosphere Model WG	22 January 2001	NCAR	15
Ocean Model WG	22 January 2001	NCAR	8
Polar Climate WG	22 January 2001	NCAR	4
4th Data Processing and Visualization Workshop	10-12 February 2002	Santa Cruz, CA	10
CCSM Advisory Board	12-13 February 2001	Washington, DC	35
Software Engineering WG	27 February 2001	Oak Ridge, TN	30
Biogeochemistry WG	29-30 March 2001	Berkeley, CA	20
5th Data Processing and Visualization Workshop	3-5 April 2001	NCAR	12
6th Data Processing and Visualization Workshop	15-17 May 2001	NCAR	12
CCSM Scientific Steering Committee	25 June 2001	Breckenridge, CO	12
6th Annual CCSM Workshop and Poster Session	26-28 June 2001	Breckenridge, CO	250
Joint CCSM Advisory Board and Scientific Steering Committee	29 June 2001	Breckenridge, CO	35
CCSM Scientific Steering Committee	27-28 November 2001	NCAR	12
7th Data Processing and Visualization Workshop	10-12 December 2001	NCAR	7
CCSM Advisory Board with CLIVAR	8-9 January 2002	Washington, DC	45
Polar Climate WG	6-8 February 2002	NCAR	18
Software Engineering WG	14-15 February 2002	NCAR	28
Joint Biogeochemistry & Land Model WGs	26-28 March 2002	NCAR	75
CCSM Scientific Steering Committee	2-3 April 2002	NCAR	12
Atmosphere Model WG	3-4 April 2002	Boulder, CO	50
8th Data Processing and Visualization Workshop	14-16 May 2002	NCAR	20

CCSM Meetings	Date of Meeting	Venue of Meeting	No. of Participants
CCSM Scientific Steering Committee/ Working Group Co-Chairs/ CCSM Advisory Board	24 June 2002	Breckenridge, CO	34
7th Annual CCSM Workshop and Poster Session	25-27 June 2002	Breckenridge, CO	268
CCSM Script Tutorial	28 June 2002	NCAR, CO	62
Joint CCSM Scientific Steering Committee & CCSM Advisory Board	28 June 2002	Breckenridge, CO	35
CCSM Scientific Steering Committee	18-19 November 2002	NCAR	15
CCSM and GFDL Atmosphere Modelers	25-26 November 2002	NCAR	25
Polar Climate WG	22-23 January 2003	NCAR	22
CCSM Advisory Board	28-29 January 2003	Washington, DC	40
Software Engineering WG	4-5 February 2003	NCAR	28
Chemistry Climate Interactions Workshop	10-12 February 2003	Santa Fe, NM	22
Land Model WG	25-26 February 2003	NCAR	22
Joint Atmosphere Model & Climate Variability WG	6-7 March 2003	Boulder, CO	80
Joint Paleoclimate and Ocean Model WGs	19-21 March 2003	Boulder (cancelled–weather)	
CCSM/CLIVAR Workshop on Tropical Biases	28-30 May 2003	Princeton, NJ	50

b. Free Availability of CCSM Code and Output Data

The complete CSM software was first released on the Web in June 1996. CSM1.1 was released in the fall of 1996. CSM1.2 was released on the Web in July 1998. This code implemented the same algorithms as in CSM1.1 but with considerable improvements to the code, build procedures, and run scripts. One notable improvement was that CSM1.2 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.ccsm.ucar.edu/models. Output data from the primary CCSM simulations are available on the Web, from the NCAR Mass Storage System, and from the DOE Program for Climate Model Diagnosis and Intercomparison (PCMDI). 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.

XII. List of Acronyms

ACC	Antarctic Circumpolar Current
AGCMs	atmospheric general circulation models
AM2	GFDL atmospheric model
AMIP	Atmospheric Model Intercomparison Project
AML	atmospheric mixed-layer model
AMWG	Atmosphere Model Working Group
BATS	biosphere-atmosphere transfer scheme
BGCWG	Biogeochemistry Working Group
C4MIP	Coupled Carbon Cycle Climate Model Intercomparison Project
CAB	CCSM Advisory Board (formerly CMAP Scientific Advisory Council)
CAM2	CCSM Atmosphere Model version 2
CASA	Carnegie-Ames-Stanford Approach
CCA	Common Component Architecture (DOE)
CCM3	Community Climate Model version 3
CCSM	Community Climate System Model
CCSP	Climate Change Science Program
CCWG	Climate Change Working Group
CFCs	chlorofluorocarbons
CGD	Climate and Global Dynamics Division (NCAR)
CLM	Community Land Model
CMAP	Climate Modeling, Analysis, and Prediction Program (NSF)
CMAP	Climate Prediction Center Merged Analysis of Precipitation (NOAA)
CMIP	Coupled Model Intercomparison Project
CO_2	carbon dioxide
CPL3,5	coupler version 3, coupler version 5
CRB	Change Review Board
CRIEPI	Central Research Institute of Electric Power Industry, Japan
CSEG	CCSM Software Engineering Group (CGD)
CSIM	CCSM Sea Ice Model
CSM1	Climate System Model version 1
CVS	Concurrent Versioning System
CVWG	Climate Variability Working Group
DOE	U.S. Department of Energy

ENSO	El Niño–Southern Oscillation
ESMF	Earth System Modeling Framework (NASA)
GFDL	Geophysical Fluid Dynamics Laboratory (NOAA)
GUI	graphical user interface
HadISST	Hadley Centre Sea Ice and SST data sets
IAP94	Institute of Atmospheric Physics Land Surface Model version 1994
IGBP	International Geosphere-Biosphere Programme
IPCC	Intergovernmental Panel on Climate Change
IRI	International Research Institute for climate prediction
ISCCP	International Satellite Cloud Climatology Program
ITCZ	Intertropical Convergence Zone
KPP	K-profile Parameterization
LANL	Los Alamos National Laboratory (DOE)
LMWG	Land Model Working Group
LSM	Land Surface Model
MCT	model coupling toolkit
MOC	Meridional Overturning Circulation
MOZART	Model of Ozone and Related Trace Species
MPDATA	Multi-dimensional Positive Definite Advection Transport Algorithm
MPI	Message Passing Interface
NAO	North Atlantic Oscillation
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NCEP	National Centers for Environmental Prediction
NCOM	NCAR CSM Ocean Model
NERSC	National Energy Research Scientific Computing Center (DOE)
NOAA	National Oceanic and Atmospheric Administration
NPP	net primary production
NSF	National Science Foundation
NVAP	NASA Water Vapor Project
OCMIP	Ocean Carbon Model Intercomparison Project
ODA	ocean data assimilation products
OMWG	Ocean Model Working Group
PCM	Parallel Climate Model
PCMDI	Program for Climate Model Diagnosis and Intercomparison (DOE)
PCTM	Parallel Climate Transition Model
PCWG	Polar Climate Working Group
PDO	Pacific Decadal Oscillation
PFT	plant functional type

POGA	Pacific Ocean Global Atmosphere
POP	Parallel Ocean Program
RCM	regional climate model
ROMS	Regional Oceanic Modeling System
SciDAC	Scientific Discovery through Advanced Computing (DOE)
SEWG	Software Engineering Working Group
SSC	Scientific Steering Committee
SSTs	sea surface temperatures
UCAR	University Corporation for Atmospheric Research
UCLA	University of California, Los Angeles
UKMO	United Kingdom Meteorological Office
WACCM	Whole Atmosphere Community Climate Model
WCRP	World Climate Research Programme
WGNE	Working Group on Numerical Experimentation

XIII. List of Collaborating Institutions

Argonne National Laboratory

Bureau of Meteorology Research Centre (BMRC), Melbourne, Australia

California Institute of Technology

Center for Ocean-Land-Atmosphere Studies (COLA)

Central Research Institute for the Electric Power Industry (CRIEPI), Japan

Centre National d'Etudes Spatiales (CNES), France

Colorado State University

DOE Lawrence Berkeley National Laboratory

DOE Lawrence Livermore National Laboratory

DOE Los Alamos National Laboratory

DOE Oak Ridge National Laboratory

Duke University

Fujitsu America Inc.

Georgia Institute of Technology

Idaho State University

Lamont-Doherty Earth Observatory

Max-Planck Institute

Massachusetts Institute of Technology

NASA/Goddard Institute for Space Studies

NASA/Goddard Space Flight Center

NASA/Langley Research Center

National Centers for Environmental Prediction

NOAA Climate Diagnostics Center (CDC)

NOAA Climate Monitoring and Diagnostics Laboratory (CMDL)

NOAA Cooperative Institute for Research in Environmental Sciences (CIRES)

NOAA Forecast Systems Laboratory (FSL)

NOAA Geophysical Fluid Dynamics Laboratory (GFDL)

NOAA National Climatic Data Center (NCDC)

Oregon State University

Pacific Northwest National Laboratory

Pennsylvania State University

Program for Climate Model Diagnostics and Intercomparison (PCMDI)

Purdue University

Rutgers University

Scripps Institution of Oceanography

State University of New York

Stockholm University

University of Alaska

University of Arizona

University of Bern

University of California, Berkeley

University of California, Irvine

University of California, Los Angeles

University of California, San Diego

University of California, Santa Barbara

University of California, Santa Cruz

University of Chicago

University of Colorado

University of Connecticut

University of Hawaii

University of Illinois

University of Indiana - Justin School

University of Maryland

University of Melbourne, Australia

University of Miami

University of Michigan

University of Montana

University of Sheffield

University of Southern California

University of Texas

University of Washington

University of Wisconsin-Madison

U.S. Army Cold Regions Research and Engineering Laboratory

Woods Hole Oceanographic Institution