The Community Climate System Model

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ABSTRACT

The Community Climate System Model (CCSM) has been created to represent the principal components of the climate system and their interactions. Development and applications of the model are carried out by the U.S. climate research community, thus taking advantage of both wide intellectual participation and computing capabilities beyond those available to most individual U.S. institutions. This article outlines the history of the CCSM, its current capabilities, and plans for its future development and applications, with the goal of providing a summary useful to present and future users.

The initial version of the CCSM included atmosphere and ocean general circulation models, a land surface model that was grafted onto the atmosphere model, a sea-ice model, and a "flux coupler" that facilitates information exchanges among the component models with their differing grids. This version of the model produced a successful 300-yr simulation of the current climate without artificial flux adjustments. The model was then used to perform a coupled simulation in which the atmospheric CO_2 concentration increased by 1% per year.

In this version of the coupled model, the ocean salinity and deep-ocean temperature slowly drifted away from observed values. A subsequent correction to the roughness length used for sea ice significantly reduced these errors. An updated version of the CCSM was used to perform three simulations of the twentieth century's climate, and several projections of the climate of the twenty-first century.

The CCSM's simulation of the tropical ocean circulation has been significantly improved by reducing the background vertical diffusivity and incorporating an anisotropic horizontal viscosity tensor. The meridional resolution of the ocean model was also refined near the equator. These changes have resulted in a greatly improved simulation of both the Pacific equatorial undercurrent and the surface countercurrents. The interannual variability of the sea surface temperature in the central and eastern tropical Pacific is also more realistic in simulations with the updated model.

Scientific challenges to be addressed with future versions of the CCSM include realistic simulation of the whole atmosphere, including the middle and upper atmosphere, as well as the troposphere; simulation of changes in the chemical composition of the atmosphere through the incorporation of an integrated chemistry model; inclusion of global, prognostic biogeochemical components for land, ocean, and atmosphere; simulations of past climates, including times of extensive continental glaciation as well as times with little or no ice; studies of natural climate variability on seasonal-to-centennial timescales; and investigations of anthropogenic climate change. In order to make such studies possible, work is under way to improve all components of the model. Plans call for a new version of the CCSM to be released in 2002. Planned studies with the CCSM will require much more computer power than is currently available.

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1. Introduction

Climate involves a complex interplay of physical, chemical, and biological processes of the atmosphere, ocean, sea ice, and land surface. Establishing the system's response to changes in anthropogenic emissions of carbon dioxide, reactive trace gases, and land use requires a coupled-climate-system approach.

The development of a comprehensive climate system model that accurately represents the principal components of the climate system and their interactions requires both wide intellectual participation and computing capabilities beyond those available to most (if any) individual U.S. institutions. Wide participation is facilitated by a framework for coupling existing and future component models developed at multiple institutions, which permits rapid exploration of alternate formulations, which is receptive to components of varying complexity and of varying resolutions, and which balances scientific needs with resource availability. It must accommodate an active program of simulations and evaluations, evolving so as to address scientific issues and problems of national and international policy interest. The Community Climate System Model (CCSM), which is the subject of this paper, has been created to fill this need. The purpose of this paper is to outline the history of the CCSM, its current capabilities, and plans for its future development and applications, with the goal of providing a summary useful to present and future users.

TABLE 1. Summary of acronyms used in this paper.

ACACIA	A Consortium for the Application of Climate Impact Assessments
AMIP	Atmospheric Model Intercomparison Project
CCM	Community Climate Model
CCSM	Community Climate System Model
CFCs	Chlorofluorocarbons
CH_4	Methane
CICE	Sea-ice model developed at Los Alamos National Laboratory
CLIVAR	Climate Variability and Predictability program
CLM	Common Land Model
CO_2	Carbon dioxide
CRIEPI	Central Research Institute of Electric Power Industry, Japan
CSM	Climate System Model
DOE	U.S. Department of Energy
ENSO	El Niño–Southern Oscillation
EOF	Empirical orthogonal function
GCM	General circulation model
IGBP	International Geosphere–Biosphere Programme
IPCC	Intergovernmental Panel on Climate Change
LSM	Current version of the CCSM Land Surface Model
LTE	Local thermodynamic equilibrium
MACCM3	Middle-atmosphere version of CCM3
MJO	Madden–Julian oscillation
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NOAA	National Oceanic and Atmospheric Administration
NSF	National Science Foundation
PBL	Planetary boundary layer
POP	Parallel Ocean Program
SST	Sea surface temperature
TIME	Thermosphere–ionosphere–mesosphere–electrodynamics
WCRP	World Climate Research Programme

The Community Climate Model (CCM)[1] was created by the National Center for Atmospheric Research (NCAR) in 1983, as a freely available global atmospheric model, for use by the wider climate research community. The first version of the CCM was based on a model developed by K. Puri and colleagues at the Australian Bureau of Meteorology Research and the U.S. Geophysical Fluid Dynamics Laboratory. After being transferred to NCAR, the model was endowed with an NCAR-developed radiation parameterization, and made available for use by the community, under the name CCM0A. The formulation of the CCM has steadily improved over the past two decades, computers powerful enough to run the model have become relatively inexpensive and widely available, and usage of the model has become widespread in the university community, and at some national laboratories. An account of the events that led to the creation of the CCM is given by Anthes (1997).

Up to the mid-1990s, the CCM was of limited use as a climate model because it did not include submodels of the global ocean and sea ice. The first plan to develop and use a climate system model (CSM) including the atmosphere, land surface, ocean, and sea ice was proposed to the National Science Foundation (NSF) in 1994. The plan was to focus initially on the physical aspects of the climate system, and then in a subsequent version to add other components such as

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[1] This paper makes use of many acronyms, which are summarized in Table 1.

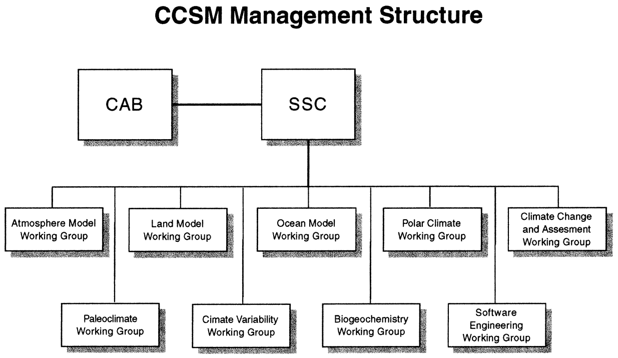

FIG. 1. Organizational diagram. The CAB is the CCSM Advisory Board. The SSC is the CCSM Scientific Steering Committee. The working group structure shown is correct as of late 2000, but has evolved over time and will continue to evolve.

biogeochemistry. The first version of the CSM was developed by the NCAR staff and made available to the scientific community. A new governance structure was then adopted encouraging the scientific community at large to participate in all aspects of the CSM, including model development. This makes the CSM the first true community climate model, if by definition a community model is developed by the community, is freely available for use by the community, and is subjected to scientific scrutiny by the community. A scientific steering committee was formed to lead the CSM activity, Working groups were organized to develop the model and analyze its results, and a CSM Advisory Board was created (Fig. 1). The Department of Energy (DOE), the National Aeronautics and Space Administration (NASA), and the National Oceanic and Atmospheric Administration (NOAA), among others, have developed strong interests in the CSM.

In May 1996, the inaugural CSM Workshop was held in Breckenridge, Colorado. At this workshop, the CSM's formulation and the results of an equilibrium climate simulation were presented. The workshop marked the beginning of the second phase of CSM, in which the U.S. national scientific community is fully involved as described above. To emphasize this full involvement, the CSM has recently been renamed as the Community Climate System Model, and the new name will be used throughout the rest of this paper, even when discussing earlier versions of the model. Recognizing, nevertheless, that some users will need to distinguish among various versions of the model, we provide an abbreviated summary list in Table 2.

The simple but ambitious long-term goals of the CCSM project are

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

TABLE 2. Versions of the Community Climate System Model.

Date	Version	Physics and experiments
May 1996	CSM 1.0	*Journal of Climate,* Jun 1998 (Vol. 11, No. 6); 300-yr control for 1996 conditions; 130-yr 1% per year CO_2 increase
Jun 1998	CSM 1.3	Corrected air–ice drag coefficient; prognostic liquid water formulation; many atmospheric gases included in radiative transfer parameterization; 270-yr control for 1870 conditions (Boville et al. 2001); 3 twentieth century simulations; 5 twenty-first century simulations
Jun 1999	PaleoCSM	T31 CCM3 and ×3 ocean model; ocean anisotropic horizontal viscosity, and enhanced resolution at the equator; 200-yr control for 1980 conditions; 50-yr run for conditions of the last glacial maximum; 100-yr run for mid-Cretaceous conditions
Jan 2002	CCSM-2	Improved components and coupler

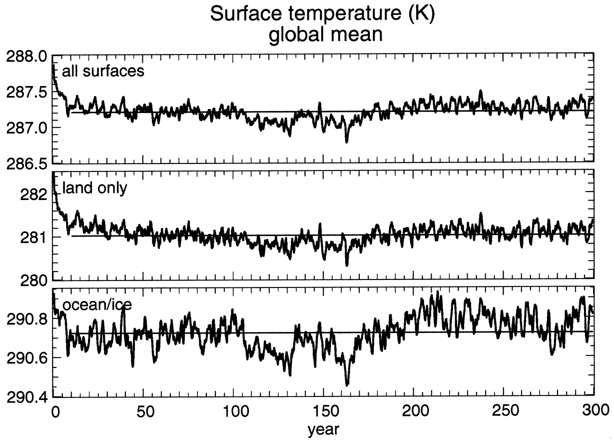

FIG. 2. Twelve-month running means of surface temperature globally averaged over (top) all surfaces, (middle) land only, and (bottom) both ocean and sea ice. The mean of each series from years 11 to 300 is indicated by the horizontal line.

This paper summarizes the achievements to date, and outlines our present view of the current state of the CCSM effort and where the project is going over the next five years, including our plans for both model development and numerical experimentation.

2. Early development and applications of the CCSM

The initial version of the CCSM, which was released in July 1996, included atmosphere and ocean general circulation models (GCMs), a land surface model that was grafted onto the atmosphere model, a sea-ice model, and a "flux coupler" that facilitates information exchanges among the component models with their differing grids. In addition, a tropical Pacific Ocean model was included. Input data files could be substituted for each CCSM component, making it possible, for example, to drive the ocean model with input data based on observations.

The atmosphere was forced for several years with climatological sea surface temperatures (SSTs). The results were stored, and then used to force the ocean and sea-ice models for several decades. An acceleration technique was used to spin up the deep ocean for an effective period of 500 simulated years. The fully coupled model was then integrated for 300 simulated years. Analyses of the results from this experiment have been published in a special issue of the *Journal of Climate* (dated Jun 1998, Vol. 11, No. 6).

In this simulation, the global annual mean surface temperature drifts by 0.7 K over the first 5–10 yr of the simulation, and is remarkably stable afterward. Figure 2 (from Boville and Gent 1998) shows 12-month running means of surface temperature globally averaged over all surfaces. The mean of each series from years 11 to 300 is indicated by the horizontal line. The initial adjustment is largely due to a decrease of 1.5 K in the land temperatures, which occurred because a generic initial condition was inadvertently used in the Land Surface Model, version 1 (LSM 1), instead of the equilibrated state from the end of the Community Climate Model, version 3 (CCM3)/ LSM 1 simulation. The ocean temperatures change rapidly in the first few months of the simulation; the initial month is approximately 0.2 K warmer than any subsequent month. The coupled simulation exhibits strong multiyear variability, but there are no systematic surface temperature trends after year 10. The trends in land and ocean/sea-ice temperatures, determined by least squares fits for years 11 to 299, are 0.03 K century^{-1}, which is small compared to the standard deviations of their annual means, which are 0.2 and 0.07 K, respectively.

Over much of the globe, the annual-mean simulated SSTs are within 1 K of those observed. A notable exception is that the SSTs off the west coasts of North America, South America, and Africa are too warm by 2–3 K because of an underprediction of marine-stratus cloud amount in those regions. In high northern latitudes, a shift in the Gulf Stream is apparent with a warm bias off Labrador, and the SSTs are too cold near Norway and in the North Pacific. These biases are accompanied by shifts in the ice distribution. The high-latitude Southern Ocean is slightly too warm, although the largest difference from the climatology is associated with errors in the path of the Antarctic Circumpolar Current over large ridges in bottom topography.

The area covered by sea ice in the Northern Hemisphere increases for the first 20 yr of the coupled simulation, and then stabilizes at a level about 15% higher than observed. The excess is somewhat larger in winter than in summer. In the 80-yr period from years 110 to 190, the winter sea-ice areas increase, and then they return to the earlier, somewhat too large value. The increased winter sea ice in the 80-yr period is quite thin and does not significantly augment the total sea-ice volume.

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

Overall the results of this initial coupled experiment were very encouraging. We were particularly encouraged to obtain a realistic, stable pattern of surface temperature without using flux adjustments. A full discussion can be found in the June 1998 issue of the *Journal of Climate* (Vol. 11, No. 6).

Simulation of transient CO_2 increase

Following the control run described above, we performed a coupled simulation in which the atmospheric carbon dioxide (CO_2) concentration increased by 1% per year. This work was carried out in collaboration with scientists from Japan's Central Research Institute of Electric Power Industry (CRIEPI). The initial conditions were taken from year 15 of the 300-yr control run (shown as year 10 in Fig. 3). The CO_2 concentration was held fixed at 355 ppmv for 10 yr. The CO_2 was then increased at 1% per year for 115 years, at which time the concentration had increased by slightly more than a factor of three. The results of this run are being used by CRIEPI scientists to provide boundary and forcing data for regional model simulations. Figure 3 (after Boville 1999) shows the 12-month running means of globally averaged surface temperature anomalies with respect to the mean over years 11–300 of the control simulation. After CO_2 begins increasing, at year 0, the temperature increases almost linearly, at a rate of 2.2 K century^{-1}. The temperature has increased by 1.25 K at the time of CO_2 doubling, and 2 K at the time of CO_2 tripling, consistent with a 2-K equilibrium temperature increase (for doubled CO_2) simulated by the CCM3 coupled to a slab ocean.

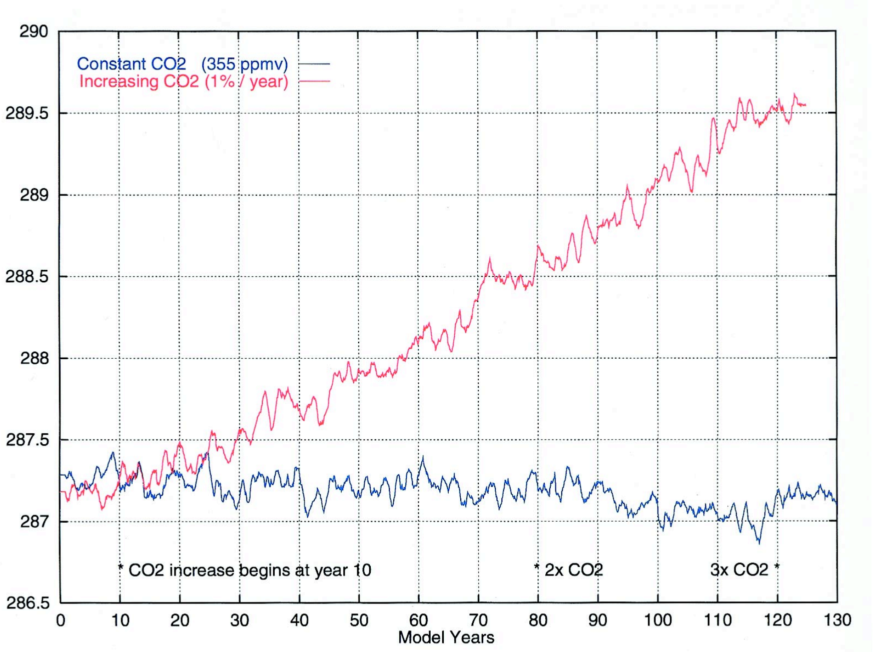

FIG. 3. Twelve-month running means of globally averaged surface temperature anomaly, with respect to years 11–300 of the control simulation, for the control simulation (blue) and the increasing CO_2 experiment (red).

3. Recent CCSM development and applications

a. *Corrected sea-ice roughness*

J. Weatherly (Department of the Army Cold Regions Research and Engineering Laboratory) found that the aerodynamic roughness length of sea ice used in the original CCSM simulations (40 mm) was unrealistically large. As a result, we tested the model's sensitivity to a smaller value (0.5 mm) that is appropriate for relatively smooth first-year sea ice. The change had a modest impact on the ice distribution in either hemisphere, but it significantly reduced the rate of Antarctic deep-water formation, which remains too large but is now closer to that in the real ocean. As a result, the drift of the deep-ocean salinity was reduced by an order of magnitude, and the drift in deep-ocean temperatures was also reduced, although it continues to be noticeable. Figure 4 (from Boville et al. 2001) shows the deep-ocean temperature and salinity as functions of time during the spinup and coupled phases of the original 300-yr coupled run with an aerodynamic roughness length for sea ice of 40 mm (black curves), and for a new 25-yr coupled run with an aerodynamic roughness length for sea ice of 0.5 mm (red curves).

b. *Simulations of the climates of the twentieth and twenty-first centuries*

This updated version of the CCSM (listed in Table 2 as CSM 1.3) was used to perform three simulations of the twentieth century's climate. A new spinup and a long (currently 270 yr) control run of the coupled model were carried out using 1870 conditions

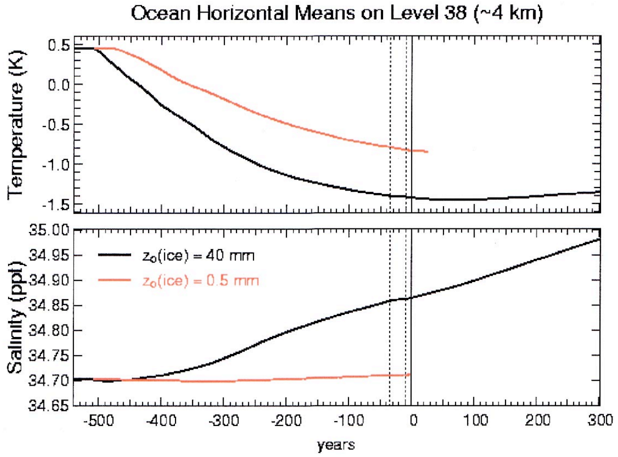

FIG. 4. Deep-ocean temperature and salinity as a function of time during the spinup and coupled phases of the original 300-yr coupled run with an aerodynamic roughness length for sea ice (z_0) of 40 mm (black curves) and for a new 25-yr coupled run with a $z_0 = 0.5$ mm (red curves). The initial values are realistic for these fields.

(Boville et al. 2001). We then applied time-varying reconstructions of atmospheric concentrations of sulfate aerosol, CO_2, ozone (O_3), methane (CH_4), nitrous oxide (N_2O), and chlorofluorocarbons CFC11 and CFC12, as observed during the twentieth century (Kiehl et al. 1999, 2000; Dai et al. 2001). The latter four gases were advected in the CCSM, and CFC11 concentrations were scaled to account, in terms of total radiative forcing, for the effects of other halocarbons. The three simulations of the twentieth century differed only in their initial conditions, which were taken from different years of the control simulation.

Results show that the globally averaged temperature increased by about 0.6 K between the late nineteenth century and the 1990s (0.7 K in 2000), as observed. Figure 5 shows 5-year running means of the globally averaged surface air (2 m) temperature anomalies (blue) with respect to the control simulation (black). Also shown is the observed global temperature record since 1860 (green). However the simulations do not capture the local minimum in the observed temperature record during the 1940s, which may have been caused, in part, by decreased solar irradiance. All three simulations reproduce the observed temperature increase since 1970.

Several simulations of the climate of the twenty-first century have been carried out, using the results of the twentieth century simulation (expt 1) described above as initial condition. Two scenarios were developed under the auspices of "A Consortium for the Application of Climate Impact Assessments" (ACACIA) in support of the U.S. National Climate Assessment: a "business as usual" scenario, in which greenhouse gases are assumed to increase with no economic constraint, and a "policy limited" scenario, in which emissions are presumed to be constrained so that the concentration of CO_2 in the atmosphere levels off at 550 ppmv shortly after 2100 (Dai et al. 2001). In addition, experiments were performed using three scenarios (A1, A2, and B2) from the Intergovernmental Panel on Climate Change (IPCC) scenario for Third Assessment Report. Figure 6 shows the observed global temperature record since 1860, and a 5-yr running mean surface air (2 m) temperature from the twentieth century simulation and the 5 twenty-first century simulations. At the end of the twentieth century, the temperature has increased by 0.7 K with respect to the control simulation. The temperature increase at the end of the twenty-first century spans the range of 2–2.9 K with respect to preindustrial conditions, or 1.3–2.2 K

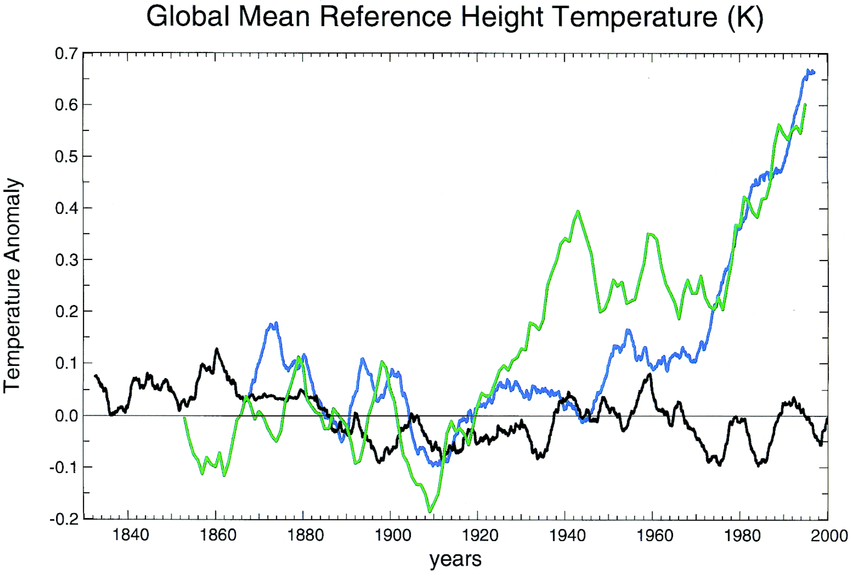

FIG. 5. Five-year running global averaged surface air (2 m) temperature anomalies for a twentieth century simulation (blue). The anomalies are differences from the time mean of the 1870 control simulation, and the anomalies from this simulation are shown in black. Also shown are the anomalies (with respect to the mean from 1861 to 1900) for the observed global temperature record since 1860 (green).

with respect to present-day conditions, with the smallest increase occurring in the ACACIA policy-limited scenario and the largest increase occurring in the IPCC A2 scenario. The range of temperature increase is consistent with the different concentrations of greenhouse gases in the various scenarios.

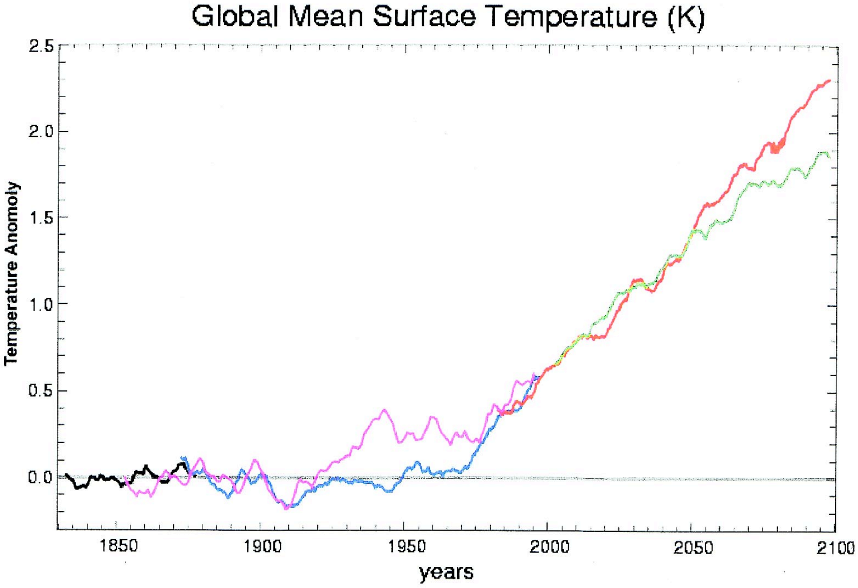

FIG. 6. Anomaly (with respect to mean from 1861 to 1900) in global mean surface air temperature for: observed 20th century (magenta), simulated 20th century (blue), simulated 21st century assuming business as usual (red) and policy limited CO_2 growth (green).

c. *Coarse-resolution simulation of ENSO*

The CCSM's simulation of the tropical ocean circulation has been significantly improved by reducing the background vertical diffusivity and incorporating an anisotropic horizontal viscosity tensor with greatly reduced cross-flow diffusion (Large et al. 2001). The meridional resolution of the ocean model was also refined to 0.9° between 10°S and 10°N, while remaining nominally 3° elsewhere; this version of the ocean model is referred to as the ×3 model, for short.

The revised ×3 ocean and sea-ice components described above have been coupled to a T31 version of the CCSM atmosphere model to produce a new paleoclimate version of the CCSM (see PaleoCSM listing in Table 2). As seen in the paleoclimate simulations performed by B. Otto-Bliesner and colleagues (NCAR), these changes have resulted in a greatly improved simulation of both the Pacific equatorial undercurrent and the surface countercurrents. Figure 7 (from Large et al. 2001) shows the equatorial Pacific simulation, at 140°W, from the original ocean model (top panel) and the revised ocean model (bottom panel). A realistic speed of the undercurrent is about 1 m s^{-1}, as in the new model. Tests show that the improvements are primarily due to the reduced background diffusivity and anisotropic horizontal viscosity in the ocean model.

The interannual variability of SSTs in the central and eastern tropical Pacific is also more realistic in simulations with the new model. Figure 8 (from Otto-Bliesner and Brady 2001a) shows the Niño-3 and Niño-4 SST anomalies and the first empirical orthogonal function (EOF) pattern of tropical Pacific SSTs for a 50-yr period in a coupled simulation of preindustrial conditions. The simulated Niño-3 standard deviation is 0.67 K, which is comparable to observed values for 1950–79 of 0.70 K with enhanced power at periods of 3–4 yr. The first EOF of the simulated SSTs shows the familiar El Niño pattern, with one sign in the central and eastern tropical Pacific, and the other in the North and South Pacific. Figure 9 (from Meehl et al. 2001) shows Niño-3 amplitude (top panel) and Niño-4 amplitude (bottom panel) versus ocean model background vertical diffusivity for several coupled simulations. The solid lines represent Niño-3 and Niño-4 amplitudes for the observations from 1950 to 1979 and 1950 to 1998. It is clear that the background vertical diffusivity needs to be close to 0.1 cm^2 s^{-1} in order that the amplitude of the Niño-3 variability matches that seen in the observations. A realistic amplitude of Niño-4 variability is also obtained with this value of the background vertical diffusivity.

4. Scientific challenges for the CCSM

a. *Middle atmosphere*

The middle atmosphere is an important component of the climate system. Recently, Thompson and Wallace (2000) have pointed out that the leading EOF of surface pressure variability in the Northern Hemisphere, the "Arctic oscillation," is strongly correlated with nearly zonal symmetric variability extending

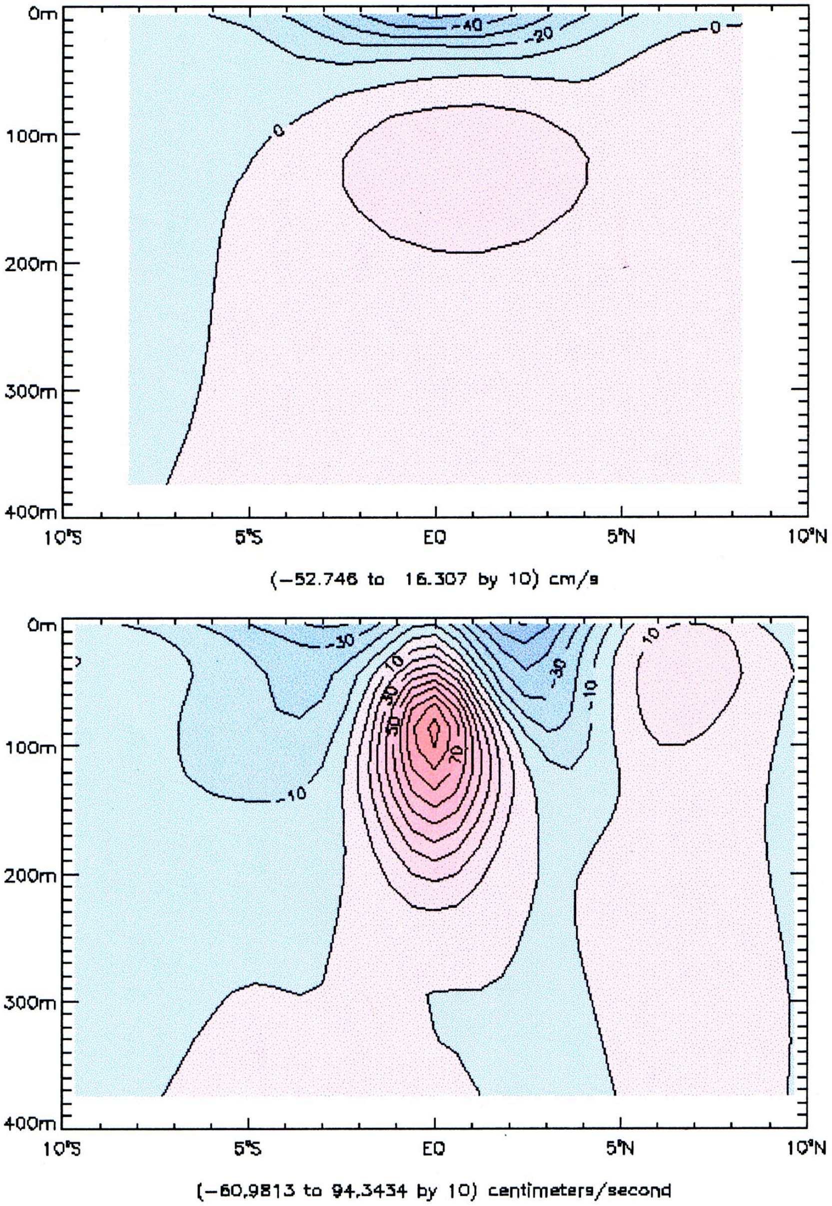

FIG. 7. The annual-mean zonal velocity at 140°W in the equatorial Pacific from (top) the original CSM ocean component and (bottom) the revised ocean model. A realistic value for the undercurrent is about 1 m s^{-1}, as in the new model.

deep into the stratosphere. Boville (1984) showed that changes in the stratospheric circulation can have a significant impact on the troposphere, altering planetary wave structures and storm track positions. Shindell et al. (2001) suggest that the climate sensitivity to increasing greenhouse gases may be different when the stratosphere is better represented.

The climate impacts of changes in the temperature, circulation, and ozone concentration of the stratosphere, mesosphere, and thermosphere are not well understood. Solar irradiance variations may affect climate variability, while greenhouse and ozone destroying gases may affect both the mean climate and its variability. Determining whether these middle- and upper-atmosphere effects have significant impact on the lower atmosphere will require models extending from the surface into the thermosphere and including ozone chemistry.

The expected cooling of the stratosphere due to increasing CO_2 concentrations is much larger than the expected increase in surface and tropospheric temperatures. Because ozone chemistry is temperature dependent, changes in stratosphere temperatures will produce changes in stratospheric ozone, regardless of changes in the circulation, or changes in the sources of chemical constituents that destroy ozone. Current climate models do not adequately represent the stratosphere and do not typically include feedbacks between ozone and dynamics. However, climate sensitivity may be different when the model stratosphere includes better ozone chemistry.

Solar irradiance variations may be an important contributing cause of climate variability. In fact, it has been suggested that much of the variability in surface temperatures over the last several centuries can be explained by variations in solar irradiance (e.g., Hoyt and Schatten 1993). While much of the observed variation in total irradiance over the solar cycle occurs at visible wavelengths, the variations at shorter wavelengths are more extreme, reaching 100% in the extreme ultraviolet (Lean and Rind 1998). Radiation at short wavelengths cannot penetrate into the troposphere, but can cause significant changes in temperature and ozone in the upper stratosphere, mesosphere, and thermosphere.

The current middle-atmosphere version of CCM3 (MACCM3) extends from the earth's surface to 84 km. The radiation parameterizations employed by MACCM3 become inaccurate above about 65 km,

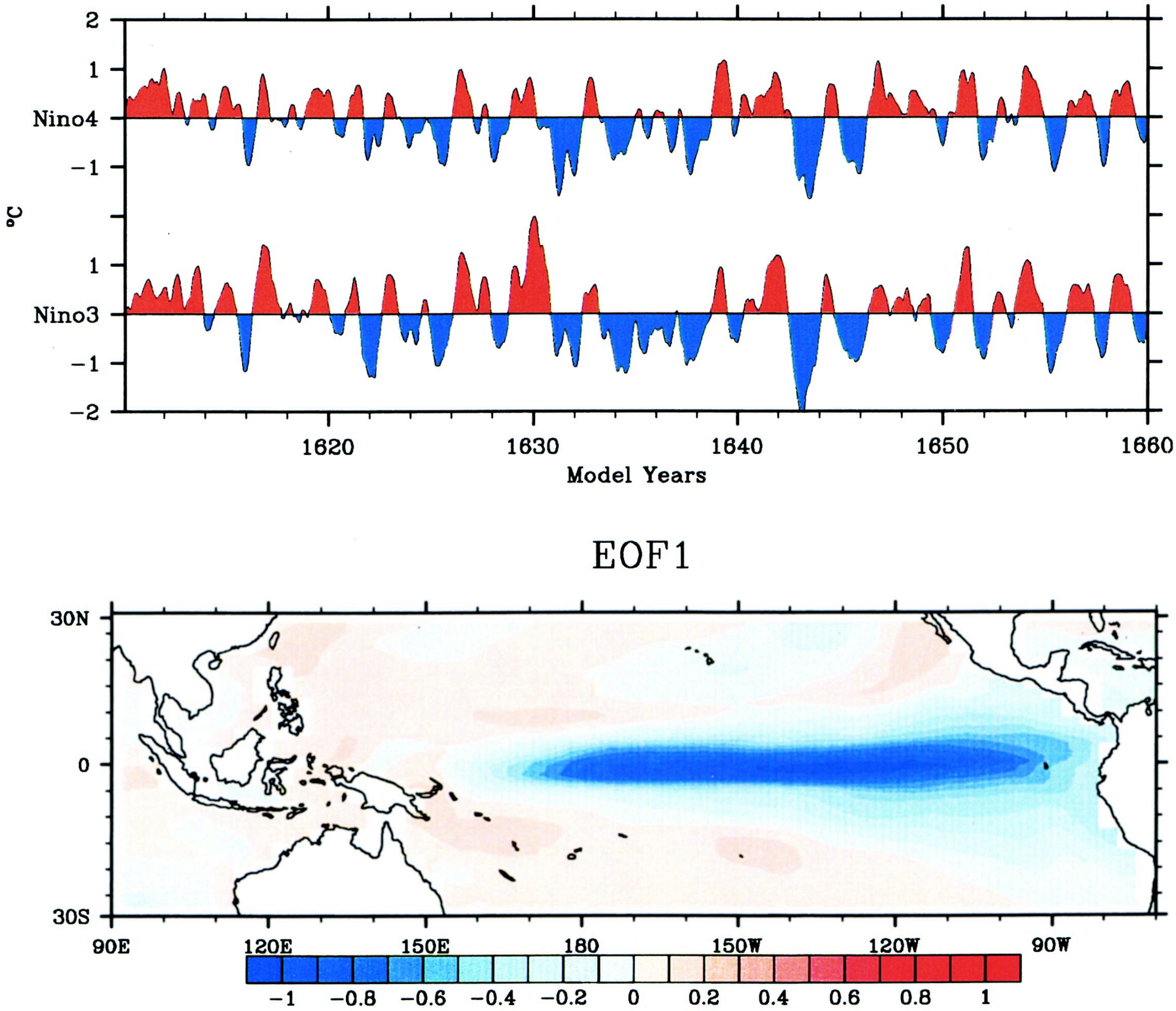

FIG. 8. Tropical Pacific SST variability simulated with a recent version of the CCSM. (top) Monthly mean SST anomalies averaged over the Niño-3 (5°N–5°S, 150°E–90°W) and Niño-4 (5°N–5°S, 160°E–160°W) regions with a five-month boxcar smoother applied. (bottom) First EOF of monthly mean SST anomalies.

largely due to the breakdown of local thermodynamic equilibrium (LTE). However, the dynamics of the upper stratosphere and lower mesosphere are strongly forced by gravity waves that propagate up from the troposphere and break between 65 and 100 km, depositing energy and momentum (Haynes et al. 1991; Garcia and Boville 1994). The MACCM3 resolves at least part of the gravity-wave-breaking region in all seasons but does not extend far into the non-LTE region.

The CCSM atmosphere model should be extended to span the atmospheric column from the troposphere through the thermosphere, in order to be able to address a wide range of new problems dealing with couplings between widely separated layers of the atmosphere. At present, work is under way to extend MACCM3 upward to the turbopause (~100 km). This will require incorporating new physics and chemistry for investigation of processes operating in the upper mesosphere and lower thermosphere, as well as couplings between atmospheric regions. The resulting model will form the basis for adding further thermospheric physics and chemistry, much of which is currently operating in the thermosphere–ionosphere–mesosphere–electrodynamics (TIME) GCM, to allow the model to be extended upward for several hundred kilometers, replacing the TIME GCM as a community model for upper-atmosphere research. New satellite data for this region will become available over the next few years, notably from the Thermosphere–Ionosphere–

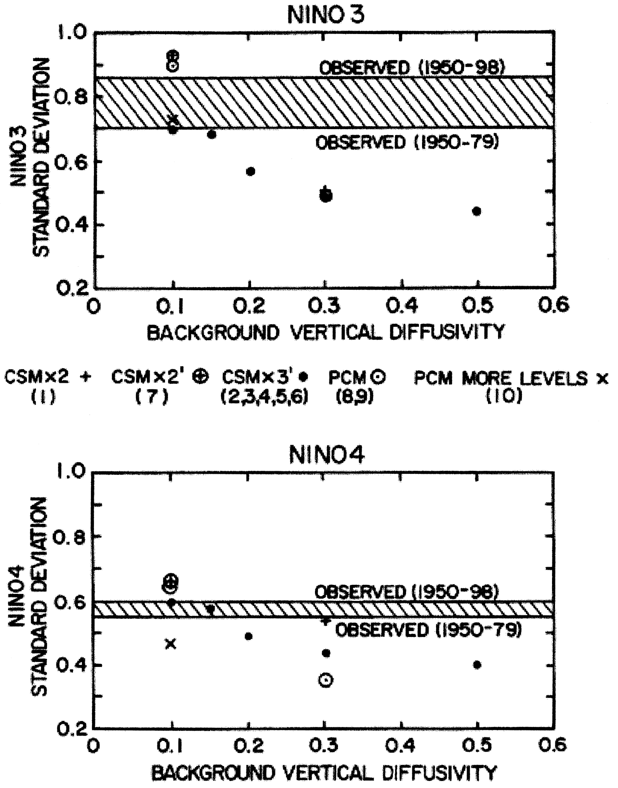

FIG. 9. (top) Niño-3 amplitude and (bottom) Niño-4 amplitude vs ocean model background vertical diffusivity for a coupled simulation. The solid lines represent Niño-3 and Niño-4 amplitudes for the observations from 1950 to 1979 and 1950 to 1998.

Mesosphere–Energetics-Dynamics mission and the High-Resolution Dynamics Limb Sounder. The upward-extended version of the atmospheric component of the CCSM will still be capable of coupling with the ocean and sea-ice models. A major application of the model will be to investigate the effects of solar variability on the atmosphere and climate system.

b. *Chemistry*

Changes in the chemical composition of the atmosphere are the fundamental driver of anthropogenic climate change. Observational records of the chemical composition of the atmosphere indicate dramatic anthropogenic changes in concentrations of trace gases, such as carbon dioxide, ozone, methane, nitrous oxide, and the CFCs. Moreover, vegetation can act as a natural source or sink of chemical species.

The atmospheric circulation and atmospheric physical processes strongly affect the chemical processes at work in the atmosphere. Chemical trace gases and aerosols are rapidly redistributed in the vertical by atmospheric convection. Cloud processes and properties affect aqueous-phase production rates. On the other hand, chemical processes can also affect the physical climate system. Changes in stratospheric ozone have major effects on the temperature of the stratosphere and on the transmission of ultraviolet radiation to the earth's surface. In addition, aerosols reflect and absorb radiation, and also modify cloud scattering properties—the "indirect effect." Aerosols interact with chemical processes as sites for heterogeneous reactions and by altering the actinic flux for photolysis. Changes in the amount of clouds, the amount of liquid water in clouds, and their lifetime will result in changes in chemical production and removal of species through wet deposition. Our current foci are the carbon cycle and the interactions among aerosols, clouds, and radiation.

The current CCSM relies on prescribed or highly constrained distributions of chemical species. An integrated chemistry model would allow simulation of these and other interactions between chemical species and the climate system.

c. *Biogeochemistry*

Interactions between the physical and biogeochemical climate systems under past, present, and future climates determine the carbon cycle's natural interannual variability and its response to forced decadal-to-centennial perturbations (e.g., greenhouse warming and land-use change). We are developing, evaluating, and coupling a suite of global, prognostic biogeochemical component models (land, ocean, and atmosphere) within the framework of the CCSM. Evaluation will be based on extensive data analysis and diagnostic studies for the last two decades, for which good data on atmospheric composition exist. As improved models and resources become available, the effects of other radiatively and chemically important species, such as CH_4, organic halides, and sulfur species, will be included.

About 60% of anthropogenic carbon emissions from fossil fuel burning are removed by oceanic and terrestrial sinks, each estimated to contribute about −2 petagrams of carbon per year (Schimel et al. 1995). The physical mechanism for the dissolution of excess CO_2 into the ocean is reasonably well understood if not fully quantified, but the terrestrial sink is poorly determined as a mix of forest regrowth, CO_2 and nitrogen (N) fertilization, and climate effects (Schimel et al. 1995). On interannual timescales, the absolute magnitude of the CO_2 sinks and their partitioning between land and ocean vary considerably (Rayner et al.

1999). The global carbon cycle has not been static over past millennia (Petit et al. 1999), nor is it likely to remain static in the future. Sinks will be altered by climate feedbacks and may saturate.

Our biogeochemistry research addresses the following questions: What are the controls on the interannual variability of land and ocean CO_2 sinks that have been observed over the last few decades? How does interaction with biogeochemical cycles of other elements (N, S, P, Fe) affect the behavior of the carbon cycle? How will the terrestrial and oceanic carbon cycles change with the changing climate? How will these processes and feedbacks alter the growth rate of atmospheric CO_2 and the rate of climate evolution?

The main elements controlling the evolution of the atmospheric CO_2 distribution are CO_2 transport and surface fluxes from the land and ocean: fossil fuel burning, deforestation, photosynthesis and respiration, and the air–sea flux. At present, atmospheric CO_2 transport comes directly from the CCSM atmospheric model. Existing CO_2 transport calculations from the CCM2 and CCM3, given prescribed surface CO_2 flux forcing, replicate the main features of the observed seasonal CO_2 cycles and meridional gradients at representative stations in NOAA's Climate Monitoring and Diagnostics Laboratory network. The time–space distributions of fossil fuel emissions are reasonably well constrained from historical reconstructions; the same is true for deforestation, but with significantly larger uncertainties (Houghton 1999; Houghton et al. 2000).

A new land biogeochemical model combines elements of LSM (photosynthesis, biophysics, leaf area index), the Century model (soil microbial respiration and nitrogen dynamics), and a new plant model (growth, plant respiration, allocation, nitrogen limitation). When completed, the land biogeochemical model will be coupled to the land surface model. On the ocean side, a simple, full-depth carbon biogeochemical model with diagnostic surface production has been created and implemented in the CCSM Ocean Model. A fully prognostic version is also under development. The treatment of oceanic ecological processes (upper-ocean production and export and subsurface remineralization) requires a core marine ecosystem model linked with full-depth biogeochemistry.

Biogeochemistry involves the transport of multiple "tracer" species by the ocean and the atmosphere. A series of comparisons between modeled and observed ocean tracers is under way (Doney and Hecht 2001, manuscript submitted to *J. Phys. Oceanogr.*). The realism of transport in the CCSM atmosphere model is being evaluated through participation in the International Geosphere–Biosphere Programme (IGBP)/Global Analysis, Interpretation and Modeling TransCom activity [an atmospheric transport intercomparison project; Law et al. (1996); Denning et al. (1999); http://transcom.colostate.edu/default.html], which deals with rectified tracers, which are strongly correlated with boundary mixing on both diurnal and seasonal timescales, with the transport of a passive, anthropogenic tracer species, SF_6, and with the implied spatial patterns and magnitudes of ocean and land CO_2 sinks as determined through an inversion method (Doney 1999).

We envision three experimental themes:

- *Interannual experiments.* These will investigate the causes of the atmospheric CO_2 variations since the 1980s. Terrestrial carbon models will be forced by the observed climate statistics of the period, while oceanic carbon modules will respond to the changes in circulation forced by the variations in surface exchanges of momentum, energy, and freshwater.
- *Permissible emissions experiment.* In a control run, an atmospheric CO_2 concentration scenario will be specified, and the terrestrial and oceanic carbon modules will be separately forced to estimate the uptake. In the experiment, a 1% per year CO_2 increase will be imposed. The difference between the specified growth rate and the calculated terrestrial and oceanic sinks can be interpreted as the rate of anthropogenic emissions that would maintain the specified growth rate. This experiment will also provide an estimate of the effects of climate change on carbon uptake.
- *Flying leap experiment.* A fossil fuel emission scenario is prescribed and the atmospheric radiation will be forced by the residual of the fossil fuel CO_2 after terrestrial and oceanic uptake have been accounted for. The terrestrial and oceanic carbon uptake will be calculated using prognostic carbon modules that are responsive to changes in climate and circulation. *The simulated carbon budget thus interacts with the simulated planetary energy budget.* This flying leap experiment was approved in early 1999 as a joint project between the World Climate Research Programme (WCRP) and the IGBP.

d. Paleoclimate studies

Multicentury simulations for preindustrial trace gas forcing show annual-mean globally averaged surface temperatures 1.3 K cooler than in simulations of present-day conditions. CCSM simulations have also been completed for the two Paleoclimate Modeling Intercomparison Project time periods, the mid-Holocene (6000 yr before present), and the Last Glacial Maximum (21 000 yr before present). The mid-Holocene simulation responds to changes in the latitudinal and seasonal distribution of incoming solar radiation caused by Milankovitch orbital variations with delayed sea-ice formation during the fall. The Last Glacial Maximum simulation, done in collaboration with the University of Wisconsin (Shin et al. 2001, manuscript submitted to *Climate Dyn.*), simulates changes in the ocean thermohaline circulations consistent with proxy data. Fully coupled simulations have explored deep-water source regions during the warm Cretaceous climate (80 million yr ago) when the continental configuration was much different and atmospheric levels of CO_2 were much higher than present (Otto-Bliesner and Brady 2001b).

Paleoclimate work with CCSM largely addresses decadal-to-centennial variability associated with atmosphere–ocean–ice–biosphere variations, pulses of volcanism, and solar irradiance changes. The range and nature of such climate variability over the last 500 yr will be explored by forcing the CCSM with reconstructed time series of the forcing mechanisms and comparing the results to proxy records (e.g., tree rings, corals, historical accounts, etc.) of climate change that supplement the instrumental record of climate observations.

Over the last 600 million yr, the climate of the earth has varied from times of extensive continental glaciation, when ice sheets reached as far equatorward as 40° latitude, to times with little or no ice, when alligators and turtles lived near the poles (Dawson et al. 1976). Ice cores from Greenland and Antarctica suggest that some regions underwent dramatic climate shifts in as little as 5–10 yr as the climate warmed from the Last Glacial Maximum. Proposed mechanisms include variations in atmospheric CO_2 and methane levels, changes in the geography and elevation of the continents and the ocean bathymetry, and the evolution of vegetation and the interactions of these mechanisms with orbital forcing. Key projects to be undertaken are as follows:

- *Climate of the seventeenth–eighteenth–nineteenth–twentieth centuries.* Ensembles of coupled CCSM simulations will allow evaluation of the patterns, ranges, and proposed causes of decadal-to-centennial variability and the coupling of the interlinked systems of ice, atmosphere, ocean, and biosphere in this response.
- *Glacial–interglacial climates and abrupt change.* Analyses of ice, ocean, and lake cores have documented that the climate system has fluctuated dramatically on decadal-to-centennial timescales over the last 130 000 yr. Meltwater impulses from the large Northern Hemisphere ice sheets as the climate warmed from the Last Glacial Maximum to the start of the Holocene (10 000 yr ago) have been proposed as a possible causal mechanism of these major abrupt changes. Within the coming five years, we hope to perform transient simulations spanning several millennia, which will enable evaluation of these ideas.
- *Warm climates of the last 100 million yr.* Coupled CCSM simulations will answer questions on the nature of the ocean overturning and the role of ocean heat transport in explaining these warm climates. The CCSM will be applied to ice-free, globally warm periods during the Cretaceous (66–144 million yr ago) and the early Paleogene (~60–50 million yr ago), during which times there is evidence for abrupt, extreme warming events (Zachos et al. 1993). These warm climates ended with the global cooling that occurred in the late Miocene and Pliocene—about the last 10 million yr (Ruddiman et al. 1997; Dutton and Barron 1997).

e. Climate variability

The study of natural climate variability on intraseasonal-to-centennial timescales is of intrinsic interest, and is also of paramount importance for providing information for climate-sensitive activities on seasonal to interannual timescales, and for detecting anthropogenic climate change, attributing its causes, and projecting its future course. The problem can be studied using the results of runs of the CCSM for periods from two decades to centuries. Large ensembles of such runs are extremely desirable.

The tropical atmosphere's response to SST forcing has been demonstrated to be dynamically predictable in the conventional model twin experimental design, and recent evidence suggests that seasonal mean midlatitude anomalies forced by tropical SSTs are predictable (e.g., Shukla et al. 2000). Similarly, it is well recognized that the Madden–Julian oscillation (MJO) and the El Niño–Southern Oscillation (ENSO) are at least somewhat predictable in a deterministic forecasting mode, even though their realistic simulation in long climate runs remains problematic. The deterministic reproduction of the low-frequency phenomena is vital to developing our confidence in the CCSM's ability to accurately replicate the slow physical adjustments inherent in climate variability and climate change. The dominant climate signal at interannual timescales is ENSO. Of particular interest are the relationship of ENSO to the annual cycle; the quasi-biennial and decadal variability of ENSO, with and without anthropogenic forcing; and the global response to ENSO.

How do soil moisture anomalies help to sustain anomalous and possibly predictable (e.g., Fennessy and Shukla 1999) summertime precipitation regimes? Experiments will compare the simulated summer climates in integrations that are initialized with climatological values of vegetation and soil moisture with those that use more realistic vegetation and soil moisture.

We plan a set of climate variability experiments directed toward answering specific scientific questions. In priority order, these experiments are the following:

- *Tropical Pacific SST mixed layer integration.* This 200-yr experiment will use the CCSM atmospheric model forced by observed SSTs in the tropical Pacific and coupled to a slab ocean model elsewhere, with spatially and seasonally varying slab depth. The purpose of this integration is to capture the effect of oceanic mixed layer feedbacks on atmospheric variability, while still representing the strong air–sea coupling in the tropical Pacific. In particular, this configuration will better represent the temporal persistence of midlatitude and tropical Atlantic atmospheric variability.
- *"Perfect model" Atmospheric Model Intercomparison Project (AMIP) style integration.* This 100-yr experiment will use the CCSM atmospheric model forced by SSTs from a coupled CCSM integration. It will show whether AMIP-type (Gates 1992) atmospheric GCM integrations using specified SSTs can reproduce the variability of a coupled model in a "perfect model" context.
- *High-resolution (approximately T85) AMIP-II ensemble.* This experiment will include 5–10 runs of 20 yr each, and will use a higher-resolution ensemble of atmospheric model integrations forced globally by observed SSTs. This suite of integrations will show how the variability simulated by the atmospheric model is affected by resolution.
- *Atmospheric model integrations using the Hadley Centre Global Sea–Ice and SST Climatology dataset.* This experiment will involve five runs of 100 yr each, and includes an ensemble of integrations to be used for comparisons with other modeling groups, which are planning a similar set of integrations under the auspices of the World Climate Research Program (to be referred to as the climate of the twentieth century experiments).
- *Extended climatological SST integration.* This experiment will be run using the latest version of the model and will extend the climatological annual cycle of the CCSM atmosphere model to 1000 yr. This long integration will enable an analysis of the statistical properties of the atmosphere model's internal variability.

In the analysis of the results of these experiments, our highest priorities will be

- to diagnose and suggest possible avenues to improve the component models so that the full CCSM can better simulate coupled atmosphere–ocean variability on intraseasonal, seasonal, and interannual timescales;
- to use the component models for predictability and sensitivity studies to further understanding of the nature and predictability of interannual variations of the climate system and their importance in the dynamics of longer-term climate variations and climate response to external forcing; and
- to participate in national and international model intercomparison projects to diagnose simulated climate variability and to carry out seasonal and interannual hindcasts.

f. Assessment of climate change

The development of the CCSM was motivated by the need for a comprehensive coupled model to study unforced and forced climate change. The natural variability of the CCSM is continually being compared to observations to gauge the model's ability to capture modes of variability ranging from diurnal to centennial timescales. An accurate representation of these natural modes of variability is a necessary condition to apply the model to problems associated with anthropogenic effects, since these effects can only be considered significant when they are larger than natural variability.

Externally forced climate change can occur from either natural causes or human effects. The natural external forcings include volcanic aerosols and solar variability. Research on these two forms of external natural forcing is being carried out. These studies indicate that natural forms of external forcing are important for understanding climate change in the mid–twentieth century (Ammann et al. 2000).

Externally forced climate change due to human activities is of great scientific and social interest. Observations clearly show that the chemical composition of the atmosphere has changed dramatically since the beginning of the twentieth century. Much of this change is due to energy use, with the concomitant increase in carbon dioxide and precursor gases that form tropospheric ozone. Use of fossil fuels has also led to increased injection of sulfur dioxide into the climate system. A significant amount of effort has already taken place to allow for the influence of changes in greenhouse gases and aerosols in the CCSM (Boville et al. 2001; Kiehl et al. 2000). Further research on aerosol effects on the climate system is on going, with emphasis on including other aerosol species, for example, black carbon.

Given current CCSM research in the areas of unforced and forced climate change, there is a commitment to continue to develop and apply the model to climate change and climate assessment problems. Over the next five years, there will be a need for a series of climate change ensemble simulations that will be part of coordinated studies by the IPCC, the U.S. National Assessment, and the WCRP's Climate Variability and Predictability program. Furthermore, we expect to be part of intercomparisons with other national and international modeling groups. As the models continue to develop and become more realistic, we expect to contribute to special simulations related to the missions of NSF and the DOE. Plans include the following:

- Design and carry out climate change simulations.
- Plan and coordinate for statistical analysis of the simulations with an emphasis on detection of climate change.
- Perform some simulations with higher-resolution ocean and atmospheric components in order to better capture regional climate change.

5. Ongoing and future development of the CCSM

a. Atmosphere model development

The increased use of CCSM to study chemistry–climate interactions will require advection schemes that are inherently conservative of chemical tracers; spectral models do not have this property. In addition, simulations reveal various deficiencies that are related to the use of a spectral code for the atmosphere. We are currently evaluating three candidate dynamical cores for the next atmosphere model: the present spectral model, a reduced-grid semi-Lagrangian model (Williamson and Olson 1994, 1998; Williamson 1997; Williamson et al. 1998; Williamson and Rosinski 2000), and the Lin–Rood scheme (Lin 1997; Lin and Rood 1997), which has a quasi-Lagrangian vertical coordinate. The tropospheric configuration of the next atmosphere model will use at least 50% higher horizontal resolution (equivalent to approximately T63 L30). Use of this or higher resolution will of course be contingent on the availability of sufficient computing resources.

Analyses of our model results suggest that the current model's cumulus parameterization does not allow realistic simulation of the observed temporal variability of tropical deep convection, including especially the MJO (e.g., Madden and Julian 1994). Accordingly, much current effort toward CCSM atmospheric model development is focused on the proper representation of various transient phenomena. Several investigators are currently exploring more realistic parameterizations of moist convection, and these are being tested in a suite of numerical experiments.

Because of its importance for the coupled ocean–atmosphere–land surface system, intensive study is also being focused on the surface energy budget, including the role of marine stratocumulus clouds. A closely related goal is to improve the physical linkages between the parameterizations of convection, stratiform clouds, radiation, and turbulence. This will require linking cumulus detrainment to stratiform cloud properties, linking predicted paths for liquid and ice water to cloud optical properties, and linking planetary boundary layer (PBL) stratus clouds to the PBL turbulence parameterization (e.g., Lilly 1968).

In collaboration with the University of Oslo, we have incorporated a prognostic cloud water parameterization into the model. This new parameterization, which is similar to that developed by Sundqvist (1978), more realistically couples hydrologic processes with radiative processes.

In addition, work is under way to better understand the distribution of shortwave energy between the surface and atmosphere. Recent observations suggest that climate models significantly overestimate the surface shortwave radiation (Garratt 1994; Wild et al. 1995;

Zhang et al. 1998a; Collins 1998). Implementation of an improved radiation parameterization is, therefore, a high priority.

We have tested several alternative formulations for the (indirect) effect of aerosols on the cloud drop size distribution and performed multiyear uncoupled simulations. The direct effect of sulfate aerosols was included in the radiative transfer model. The indirect effects are highly uncertain, and so they are currently being omitted from transient climate scenarios. Sulfate aerosol distributions were obtained from the interactive sulfate chemistry model of Barth et al. (2000). Three-dimensional aerosol distributions can be either specified from previous simulations or solved for interactively in the coupled model.

The concentrations of CH_4, N_2O, CFC11, and CFC12 (the principal greenhouse gases other than CO_2) can now be predicted by the model, based on specified distributions of the surface concentrations (not emissions); and loss rates are parameterized. The latter were derived from the photochemical model of the NOAA Aeronomy Laboratory.

Finally, the atmosphere model has been modified to produce network common data form output.

b. Land surface model development

The land surface model is now a separate executable (no longer contained within the atmospheric executable). A catchment basin runoff model has been developed in collaboration with the University of Texas at Austin. Tests suggest that the parameterized river runoff makes the simulated ocean salinity distribution more realistic.

The Land Model Working Group has completed a prototype, core single-column land model, designated the Common Land Model (CLM), which is intended to replace the current Land Surface Model. The CLM has three major logical elements. These are the core single-column model, the externally prescribed spatially distributed datasets needed for its boundary conditions and evaluation, and the scaling laws that map between its single point fluxes and the spatially averaged values needed by or provided by the atmosphere. Past approaches with simpler models have tended to combine these three constructs, for example, by assuming an equivalence between point and area-averaged processes or by including scaling algorithms as part of the physical parameterizations of the point model. However, separating the three elements should provide a framework that allows greater robustness across platforms, more interchangeability of codes and data between modeling groups, and greater participation by specialists involved with subissues.

The exchanges of energy, water, and momentum between the land surface and atmosphere vary rapidly because of the diurnal cycle. They strongly influence boundary layer processes and deep moist convection, which produce feedbacks. A major difficulty in land surface modeling is that many important processes, notably precipitation, occur on small spatial scales.

Land models depend on descriptions of seasonally and interannually varying vegetation cover and leaf densities, as well as maps of different types of vegetation according to their architectures, leaf morphologies, and growth rates. These vegetation types may change over decades or centuries, according to their interactions with the climate system. While vegetation type, cover, and state (e.g., active or inactive) have been prescribed in the past, the scientific questions to be addressed in the near future require modelers to specify this information either for individual years or through interactive models of the vegetation dynamics. There is still no generally accepted way to incorporate global vegetation data into a land model. Past methods have been based on descriptions of broad ecosystems, while a newer approach is to lump together broad plant functional types.

Carbon fluxes to leaves determine water fluxes from leaves (Bonan 1998; Dickinson et al. 1998). Because of this carbon dependence and a strong dependence of soil biogeochemistry on soil moisture and temperature, the land surface processes drive biogeochemical and ecological processes. Coupling of the land surface model with a terrestrial biogeochemistry model is a key goal for the near future.

NCAR scientists have developed a framework for land modeling that unifies otherwise separate land modules. Currently implemented besides the land biophysical package is (i) a parameterization for river routing as needed to provide the freshwater input to the ocean model and in the future generate lakes and wetlands, (ii) a parameterization for the injection into the atmosphere of desert dust as needed for aerosol modeling, and (iii) vegetative sources of volatile organic compounds. A major, yet to be developed, additional component is a comprehensive terrestrial biogeochemistry package.

c. Ocean model development

Ocean models for climate are run at fairly coarse resolutions, which are practical for long integrations.

At decadal and longer timescales, and for equilibrium simulations of the ocean, these models show large sensitivities to details of the representation of processes, such as deep convection, boundary layer dynamics, the effects of mesoscale eddies, and diapycnal mixing (Large et al. 1997; Gent et al. 1998). Progress in ocean modeling for climate studies must address these sensitivities.

Accordingly, the Parallel Ocean Program (POP; Smith et al. 1992), originally developed at Los Alamos National Laboratory, has been chosen as the base code for the next version of the CCSM. The model was specifically designed for parallel supercomputers, and it runs on a variety of platforms. The model's grid is twisted so that its "north pole" is over land, thus removing the north polar singularity from the ocean domain. We have ported the CCSM physics into POP and have extensively evaluated the results over the past year. In addition, as discussed earlier, we have included increased resolution in the Tropics and a new anisotropic viscosity scheme, which together have the beneficial impact of improving the equatorial current structure (i.e., much more realistic current speeds) and increasing the variability in the Tropics.

Over the coming five years, work to include the representation of ocean physics in the CCSM will include the following:

- *Interior diapycnal mixing processes*. The parameterization of interior diapycnal mixing processes, that is, those occurring outside the surface and bottom boundary layers, is still quite crude in the CCSM ocean model. More physically based schemes need to be developed, implemented, and tested in the CCSM to improve the representation of both the mean ocean state and its variability. A leading candidate for the energy source for interior mixing is the breaking of internal waves generated through the interaction of tidally generated currents with topography. Another mechanism known to be responsible for interior mixing is double diffusion (Zhang et al. 1998b).
- *Eddy lateral mixing of tracers*. In CCSM-1, the Gent–McWilliams (1990) mesoscale eddy parameterization was implemented using a constant coefficient. In reality, eddies in the ocean are strongly spatially and temporally variable. Therefore, a variable coefficient, such as the scheme proposed by Visbeck et al. (1997) needs to be evaluated. This will be particularly important at higher ocean model resolutions.
- *Eddy lateral mixing of momentum*. The anisotropic momentum mixing scheme of Large et al. (2001) has improved the equatorial currents significantly in coarse-resolution versions of the ocean model. It needs further refinement at higher resolution, such as having larger mixing in the direction of flow than perpendicular to the flow.
- *Natural surface boundary conditions on water*. The CCSM does not yet permit the exchange of mass, that is, freshwater fluxes through the sea surface. At present, freshwater fluxes must be reinterpreted as a fictitious and unphysical salinity flux before being applied to the ocean model. We will explore a more physically based specification of material fluxes.
- *Representation of topography*. Partial bottom cells (Adcroft et al. 1997) are a promising method to improve the representation of topography in a z-coordinate model framework.
- *Bottom boundary layer*. Including a bottom boundary layer scheme has been shown to improve the representation of dense overflow currents in ocean-alone simulations. This is important to obtain a realistic thermohaline circulation in the North Atlantic. Tests with a simple scheme in CCSM-1 showed only modest improvements. However, inclusion of a bottom boundary layer scheme needs to be evaluated for CCSM-2.
- *Numerical advection algorithms*. Improved advection schemes need to be evaluated that keep the advected quantity within realistic bounds. This is important for potential temperature, because otherwise it can become colder than is valid for the true equation of state. It is also important for advecting chemical quantities that are always positive; these can spuriously become negative with simpler, cheaper advection schemes.
- *Horizontal resolution*. Better understanding of the resolution dependence of the ocean model solutions is required. Topographic representation is guaranteed to improve with increased resolution. The use of eddy-permitting models in climate simulations needs to be further explored.
- *Upper-ocean model*. An upper-ocean model has been designed for use within the CCSM framework, as an alternative to the full ocean model (Danabasoglu and McWilliams 2000). The primary advantage of the upper-ocean model is its reduced spinup time, requiring a period of about 30 yr to reach an equilibrium state. Such a model can be an efficient tool for studies of coupled at-

mosphere–ocean dynamics and sensitivity to forcing fields and model parameters and for hypothesis testing about the roles of the abyssal ocean. An upper-ocean model will continue to be supported for the CCSM-2 framework.
- *Carbon cycle*. The oceanic component of the carbon cycle will be introduced into the model.

d. Sea-ice model development

In virtually every scenario of warming due to greenhouse gases run in climate models, the largest increases in temperature occur in the high latitudes, especially near the edge of the sea ice (e.g., Dai et al. 2001). Meanwhile, observations show changes in the water mass structure of the Arctic Ocean, thinning of Arctic sea ice, and major icebergs breaking off the Antarctic ice shelves. Changes in the polar climate are becoming apparent, and understanding these changes is of great importance. The CCSM needs an improved sea-ice model that reliably simulates the sea-ice processes that are important for climate and the ways these may change in the future.

Specific objectives for the sea-ice model in the next version of the CCSM are as follows:

- *Implement and test a plastic ice rheology with an elliptical yield curve that represents shear stresses as well as normal (compressive) stresses*. A sea-ice model called CICE has been developed at Los Alamos National Laboratory (Hunke and Dukowicz 1997), with an elastic–plastic ice rheology (elliptical yield curve), algorithms suitable for distributed-shared-memory computing, and using POP's grid. The CICE model is serving as a development framework for the CCSM sea-ice model.
- *Implement and test a multiple-category sea-ice thickness distribution and investigate the sensitivity of the results to the number of categories*. A multiple-category sea-ice thickness distribution with enhanced thermodynamics (but no explicit melt ponds) has been developed at the University of Washington (Bitz et al. 2001) and implemented with the CICE model discussed above.
- *Implement and test enhanced sea-ice thermodynamics*. An energy-conserving thermodynamic model that resolves the vertical temperature profile in the ice (Bitz and Lipscomb 1999) has been implemented in the thickness distribution model discussed above. The surface albedo is currently represented as a function of ice thickness, snow depth, and surface temperature that matches reasonably well with observations from the recent Surface Heat Exchange Budget for the Arctic ocean experiment (Perovich et al. 1999) where melt ponds covered a significant fraction of the surface. Efforts are under way to develop an explicit melt pond parameterization capable of representing the response of the surface to large climate changes.
- *Eliminate the spurious ice convergence encountered in CSM-1 near the North Pole, where the model grid points are closely spaced*. A viscous–plastic sea-ice model with elliptical yield curve was developed at the University of Washington (Zhang and Hibler 1997) and implemented at NCAR, running on a north polar grid. This model was used in a short-term (40-yr) integration of the fully coupled CSM, and it did not exhibit the spurious ice convergence near the North Pole. This model has been programmed for general orthogonal coordinates (e.g., the POP grid), but this program needs to be tested.
- *Test the performance of new versions of the CCSM sea-ice model using a stand-alone ice modeling framework and compare results to observations*. An ice-only modeling framework has been established at NCAR and initial integrations of the new model elements have been performed, forced by both atmospheric model output and National Centers for Environmental Prediction analyses. Preliminary analysis indicates the new framework is working.

Simplifications made in the initial version of the CCSM precluded comparisons with the observed Arctic Ocean circulation because the Bering Strait and the Canadian Archipelago were closed, and river runoff, which strongly influences the stratification of the Arctic Ocean and the high North Atlantic, was spatially and temporally distributed in a highly idealized manner. In CCSM-2, the Bering Strait will be opened, as will a channel through the Canadian Archipelago. In addition, as discussed earlier, a river runoff model will be included as part of the land surface model. These changes should enable major improvements in the simulation of the Arctic sea ice.

6. Concluding discussion

The CCSM was first released on the World Wide Web in June 1996. The source code and documentation for the component models are currently freely available from the CCSM Web site (http://www.ccsm.ucar.edu/models). Output from the primary CCSM simulations is available both on the Web and from the NCAR Mass Storage System.

The CCSM is the first climate model to be both developed and applied by a national community using pooled financial and human resources, from many institutions. It is a grand experiment, and so far the experiment appears to be going very well. The involvement of a broad community of scientists interested in climate simulation has been a key goal of the project from its inception, and this goal has been achieved.

We expect that the next five-year period will be characterized by increased model complexity and capability, with the model being used for various experiments that have not yet been attempted. These could include studies of the climatic effects of observed anthropogenic changes in land surface properties, and the consequences of climate change for ecosystem succession. There will be many important changes in the climate modeling enterprise over the next five years, including

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

In order for the U.S. national climate modeling community to make proper use of the CCSM it will be necessary to provide much more computer power than is currently available (National Research Council 2001). The CCSM is a case in point. As a result of its various enhancements, the next version of the CCSM will consume considerably more computer time per simulated year than the current version. In addition, the resolution of the model is very directly limited by the available computing power. Higher resolution would enable greatly improved simulations.

Acknowledgments. The community has made the CCSM what it is; in writing this paper, we are merely serving as their voice.

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