CESM

Community Earth System Model

Science Plan: 2009 – 2015

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Commissioned by the CESM Scientific Steering Committee:

Peter Gent, NCAR (Chairman)
David Bader, Lawrence Livermore National Laboratory
Gordon Bonan, NCAR
Christopher Bretherton, University of Washington
William Collins, Lawrence Berkeley National Laboratory
Scott Doney, Woods Hole Oceanographic Institution
Steven Ghan, Pacific Northwest National Laboratory
Jeffrey Kiehl, NCAR
William Large, NCAR
Philip Rasch, Pacific Northwest National Laboratory
Steven Vavrus, University of Wisconsin
Mariana Vertenstein, NCAR
Anjuli Bamzai, DOE (ex-officio)
Jay Fein, NSF (ex-officio)

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1) Introduction

Earth System Model development is an ongoing enterprise, with new model versions assembled and released at approximately five-year intervals. Continued development is enabled by new scientific understanding combined with increasing computational capability and capacity. It is generally agreed that the primary directions in the future will be the addition of new processes and components that are absent in current models, and using increased resolution in all components. This Science Plan defines a path to develop model versions that can be used to address societal needs such as predicting climate change on regional space scales and decadal time scales, to evaluate adaptation and mitigation strategies on decadal to centennial time scales, and to identify possible mechanisms for unintended and dramatic abrupt climate changes. As part of this plan, further integration of Earth System Modeling with Integrated Assessment should be continued, using a "system of systems" approach to fully encompass the natural and human systems involved in climate change. The combined Earth System and Integrated Assessment framework permits exploration of energy strategies, and future adaptation and mitigation options. This road map for model development aims to match anticipated improvements in scientific understanding with anticipated advancements in computational capabilities to achieve the maximum benefits of "exascale" computing in 2020.

Substantial progress has been made on incorporating the following new components into the model framework: an interactive carbon cycle, updated atmospheric chemistry component, a version in which the atmosphere component incorporates the whole atmosphere up to the lower mesosphere, rather than just the troposphere, and an early version of a new land ice component. The most widely used description of a model with these capabilities within the climate community is an Earth System Model. For this reason, the Scientific Steering Committee (SSC) decided that, when these components are ready in 2010, the project and supported model should be called the Community Earth System Model (CESM).

Using the CESM to produce decadal projections and predictions on regional spatial scales will require higher resolution components, and the ability to initialize the ocean component in the most appropriate way. Plans are to use 0.5^o resolution in the atmosphere component for the initial CESM decadal predictions. As the atmosphere resolution is increased, this highlights the idea of seamless prediction, where the same atmosphere component is used for both weather forecasting and climate simulations. At the least, this requires a common computational core for these two applications. However, increasing resolution is not a panacea to eliminate all the biases in climate model simulations. Thus, continued emphasis in the CESM project must be on the quality of the physical components to simulate coupled phenomena such as the El Nino-Southern Oscillation (ENSO). There needs to be a continued commitment to model-data evaluation to constrain the size of climate feedbacks and the climate sensitivity. Further paleoclimate studies are also necessary to test the CESM in situations very different from the Earth's present climate.

The interactive carbon cycle includes the effects of nitrogen limitation on the land carbon, land use changes due to human activity in the past, a dynamic vegetation component, and an ecosystem-biological module in the ocean component. All previous future projection runs using the CESM have been based on future estimates of the atmospheric concentrations of carbon dioxide. However, the interactive carbon cycle will change to using future estimates of carbon dioxide emissions, rather than concentrations. It will then determine internally how much carbon dioxide is taken up by the land and ocean, and consequently how much stays in the atmosphere. Thus, the interactive carbon cycle model will incorporate the positive feedback due to the carbon cycle, if the land and ocean take up less carbon dioxide in the future than they have in the past.

There are studies which suggest that the ozone levels in the southern hemisphere troposphere are influenced by the dynamics and circulation of the stratosphere. If that is the case, then an atmosphere component that only represents the troposphere cannot predict correctly the future ozone levels in the southern hemisphere, where the “ozone hole” occurs. In order that this process is represented correctly in future climate projections, the atmosphere component needs to incorporate the whole atmosphere up to the lower mesosphere. The CESM has such an atmosphere component called the Whole Atmosphere Community Climate Model (WACCM). The CESM also has an updated chemistry component that can be used to predict the future aerosol pollution in megacities over the next few decades. This relies on a much improved aerosol scheme that has already been incorporated into the atmosphere component. Both of these components are very computationally expensive, but can be used for research work and for a few future climate projection runs.

One of the biggest unknowns about the future climate over the 21st century is how much of the Greenland and Antarctic ice sheets will melt as the climate warms. This has large implications for the future sea level rise, with large consequences for the human population in low lying areas. The CESM has just formed a new Land Ice Working Group, which is now working on a new land ice component. The first version will be applied to the Greenland ice sheet, and will address how much ice will melt into the ocean for a given temperature rise. Subsequent versions will be more comprehensive, and include the interaction between ice shelves and the ocean. Such a model is needed to address the future behavior of the Antarctic ice sheet.

The CESM project is governed by the SSC, which presently has five members from NCAR and seven from the Department of Energy and US University communities. The project receives most of its funding from the Atmospheric Sciences Division at the National Science Foundation and the Office of Biological and Environmental Research at the Department of Energy. The project has oversight from an Advisory Board, which meets annually at the NSF, and reports back to NSF, DOE, and the NCAR Director.

2) Scientific Objectives of the CESM Program

DOE and NSF, as partners in the overall USA Climate Change and Science Program (CCSP), need a core model system for multiple purposes, including future projections of climate change. CESM has participation from a very large community of scientists, and peer-acceptance, which is important to ensure excellence and relevance. Major modeling programs are no longer single Principal Investigator research projects, because of the complexity of the problem and the technical sophistication of the models and computer codes. They are major technology development efforts, and are both shared research tools and major code projects. The CESM community enables access to contributions from multiple sources in an open development process that allows incorporation and testing of a wide range of ideas in a broad spectrum of disciplines. The CESM program also has a mission to foster the creative involvement of University researchers and students in the subject area, and thus contributes to the development of highly trained people for the future. The CESM program is a complement to the other major modeling programs in CCSP that are specifically oriented towards a government mission to provide decision-support information.

The scientific objectives of the CESM program are to:

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

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

c) Explore the history of Earth's climate through the application of versions of the CESM suitable for paleoclimate simulations.

d) 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.

3) History and Accomplishments of the CCSM Project

In 1993, a small group of scientists within the Climate and Global Dynamics Division of NCAR began meeting to discuss the possibility of building a new, comprehensive, coupled climate model. 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. Coupled model development 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 very significant accomplishment in the science of coupled models, because using a model without flux corrections gives much more confidence about the model's future climate projections. The first Annual Workshop was held in Breckenridge in May 1996, where results from the simulation of a 300-year control run were presented. 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. The first version of the Climate System Model, CSM1, was released to the community in June 1996, and a special issue of the Journal of Climate devoted to results from the CSM 1 was published in June 1998.

At this time it was recognized that further development of the model would require expertise in a wide range of disciplines. Also, scientists from the University community and DOE Laboratories were interested in contributing to development of the model. The result was that the project changed its name to the Community Climate System Model, and the DOE became a formal sponsor of the project. The second version of the model, CCSM 2, was released in May 2002. It contained a completely new sea-ice component that was developed from scratch by the Polar Climate Working Group, and completely revised land and ocean components. However, there were several aspects of the model, especially in the atmosphere component, that could be improved on, so it was decided to press ahead quickly to produce a third model version. The CCSM 3 was released in June 2004 in time for the 9th Annual Workshop in Santa Fe, New Mexico. It had further improvements in all the components compared to the CCSM 2. These improvements were again documented in a special issue of the Journal of Climate that contained

26 papers on results from the CCSM 3 that was published in June 2006. In addition, novel software engineering aspects of the CCSM 3 were documented in 13 papers that were published in a special issue of The International Journal of High Performance Computing Applications that appeared in the fall of 2005. This special issue reflects the importance of the software engineering aspects of the CCSM project. It is a huge challenge to keep a code base that works well across a large variety of computer platforms from a personal computer to a very large massively parallel machine, while maintaining a code that can be understood and changed by individual scientists.

The 4th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) was published in February 2007 to great acclaim, and the IPCC shared the 2007 Nobel Peace Prize. The CCSM project was a major contributor to this report in three ways. First, the CCSM 3 was used to produce control runs, and an ensemble of 20th and 21st Century runs. In fact, the CCSM project contributed more years of integration and results to the AR 4 than any other climate project or center. Second, several scientists heavily involved in the CCSM project were Contributing Lead Authors and Lead Authors on several important chapters, and so made very important contributions to the AR 4. Third, the CCSM community influenced the 4th Assessment significantly through numerous individual research papers using the CCSM that defined the scope of key scientific questions.

There are now a total of twelve Working Groups. The Atmosphere, Ocean, Land and Polar groups develop the physical components of the model, including the sea-ice component. The Biogeochemistry and Chemistry groups develop the carbon and nitrogen cycle and chemistry components. The Climate Variability and Climate Change groups analyze model output from a variety of integrations in order to validate the model variability and to document future climate projections by the model. The Paleoclimate group uses the model to study the climate of past epochs, and the Software Engineering group ensures that the model runs well on a variety of computers, passes many computing tests, etc. Over the past year, two new Working Groups have been formed. The first is the Whole Atmosphere group that both maintains the whole atmosphere version of the CESM and studies the influence of the upper and middle atmosphere on the troposphere. The second is a very new Land Ice group that is producing a component that models the Greenland and Antarctic ice sheets. This aspect of the model is new, but is extremely important if the project is to give realistic estimates of the possible future sea level rise. All the Working Groups meet twice a year, and report back to the SSC. One of the meetings is at the Annual Workshop, which has now been held every year from 1996 through 2009. Most of the Workshops have been held in Breckenridge, Colorado. The SSC and the Advisory Board also hold meetings at the Workshop. The Annual Workshop has become one of the most comprehensive annual climate modeling meetings in the United States. Workshop attendance has grown considerably over the years to more than 300 attendees.

4) Near-term Development of the CCSM 4

Development of the next version of the CCSM started soon after the release of the third version in 2004. Substantial progress had been made by June 2007, so that the SSC decided that an interim version, CCSM 3.5, should be assembled. This happened at the end of September 2007, but the version was not formally released in the sense that it wasn't made publically available and it didn't have the usual documentation. However, it was made available to scientists who were strongly contributing to model development through participation in a Working Group. CCSM 3.5 has numerous changes and improvements, which are briefly documented below, and see Gent et al. (2009).

The core of the Community Atmosphere Model (CAM) version 3.5, changed from the spectral core used in CAM 3 to the Lin-Rood finite volume core, see Lin (2004). Major changes were made to the deep convection scheme by including the effects of deep convection in the momentum equation, see Richter and Rasch (2008), and using a dilute, rather than an undilute, approximation in the plume calculation. These changes resulted in a major improvement in the simulation of ENSO in CCSM 3.5, which is documented in Neale et al. (2008). In CCSM 3, the ENSO frequency was dominated by variability at 2 years, whereas in CCSM 3.5 there is virtually no power at 2 years, and the power is between 3-6 years. In addition, the mean precipitation and double Intertropical Convergence Zone biases in the western tropical Pacific Ocean were considerably reduced, but not eliminated. A freeze-dry modification was added to the low cloud parameterization, which had the effect of reducing the amount of low cloud in the Arctic region. There are 26 vertical levels in CAM 3.5, the same as in CAM 3.

There have also been a number of changes to the ocean component of CCSM 3.5. The near-surface eddy flux parameterization has been modified to be more in line with observations, see Danabasoglu et al. (2008), and the isopycnal diffusivity is a function of space and time, see Danabasoglu and Marshall (2007). The anisotropic horizontal viscosity scheme has been changed in that the Smagorinsky term has been removed, and viscosity is now substantially smaller near the equator, see Jochum et al. (2008). The vertical mixing terms now have a term that is proportional to the tidal energy, and the advection scheme has been changed from the third-order upwind to a flux-limited Lax-Wendroff type scheme that is less diffusive. There are now 60 levels in the vertical, as opposed to 40 in CCSM 3.

The Community Land Model (CLM), version 3.5 is documented in Oleson et al. (2008) and Stockli et al. (2008). There were changes to many parts of the model hydrology, such as the surface runoff, the groundwater scheme, the frozen soil scheme, and a soil evaporation resistance was added. Other new features are a revised canopy integration, canopy interception scaling, and a plant functional type dependency on the soil moisture stress function. CLM 3.5 has a much improved representation of evapotransportation and the annual cycle of water storage, for example.

The sea ice component in CCSM 3.5 moved to the Community Ice Code, version 4.0 as its base code, which is maintained at the Los Alamos National Laboratory. This brought in improved treatments of ice ridging and snow on top of the ice. In addition, the much improved radiative transfer scheme of Briegleb and Light (2007) and a new melt pond parameterization were included.

Since the assembly of version 3.5, there have been further developments in all four physical components, but especially in the atmosphere. The Atmosphere Model Working Group has been implementing and evaluating four major changes to the CAM 3.5. The first is changing the radiation computation to use the RRTMG scheme, and the second is including the cloud microphysics scheme of (Morrison and Gettelman, 2008). The third is the modal aerosol scheme of Ghan and Liu that has been refined to use only three modes. This scheme is needed if the CCSM 4 is to include the indirect effects of aerosols. The fourth major change is to include the boundary layer parameterization and shallow convection scheme of Bretherton and Park. The Ocean Model Working Group has been implementing a new scheme to determine the effects of overflows over deep sills in the ocean, and a new parameterization of the effects of submesoscale eddies on the ocean mixed layer of Fox-Kemper et al., (2009). The Land Model Working Group has built on and refined the improvements in CLM 3.5, and the Polar Working Group has worked on further improvements to the sea-ice component, including using more realistic albedo values.

Assembly of the CCSM 4 will take place over the first part of 2009. First, a 1850 Control run that goes for several hundred years and is well balanced at the top of the atmosphere is required. Then, a 20th Century run from 1850 to 2005 has to be completed that gives a realistic simulation of the true climate over this period. When this is completed, the standard resolution version of the CCSM 4 will be defined. However, a half degree resolution version of the land and atmosphere components is needed, that will be used to make decadal climate predictions for the IPCC AR5. In addition, a low resolution CCSM 4 version is needed for Paleoclimate studies. The standard resolution version of the CCSM 4 should be ready by June, 2009, and will probably be released for public web download later in 2009. The half degree and low resolution versions should be ready later in 2009.

Once the new CAM 4 is defined, then other Working Groups can begin to finalize their components. In particular, the Chemistry and Whole Atmosphere components rely very heavily on the atmosphere component, and to a somewhat lesser extent, so do the carbon cycle/biogeochemistry component. The last additional component is the new land-ice model for ice sheets. These components will not be finished until later in 2009, and possibly released early in 2010. When this second release occurs, the CCSM 4 will become the CESM 1.

5) Scientific Questions to be Addressed

a) Interaction of the Carbon Cycle, Ecosystems and Climate

Land and ocean life can influence climate through a variety of biogeophysical and biogeochemical pathways. Interactions between climate and ecosystem processes, especially in response to human modification of ecosystems and atmospheric carbon dioxide (CO_2) growth, will likely produce a rich array of climate forcings and feedbacks that could either amplify or diminish climate change. Biota will also modulate regional patterns of climate change. Ecosystems are the focus of many carbon sequestration approaches for mitigating climate change, and are the central elements of potential climate impacts associated with food security, water resources, human health and biodiversity. However, the magnitude of these climate-biota interactions, and in some cases even the sign, are not well constrained, and are critical scientific unknowns affecting the skill of future climate projections.

Terrestrial vegetation alters the albedo of the land surface and modulates the exchange of momentum, sensible and latent heat, and water vapor across the land-atmosphere interface. Current understanding suggests negative biogeophysical climate forcing (cooling) associated with historical and future expansion of agricultural land in the mid-latitudes and positive climate forcing (warming) due to tropical deforestation. Open research questions include the extent and effects of past and present land-use change e.g., transition of natural ecosystems to agriculture and managed forestry; shifts in managed systems due to climate trends, bioenergy, and carbon sequestration; and expansion of urban and suburban areas, and the poleward migration of natural ecosystems such as the expansion of shrubs into Arctic tundra ecosystems. In the ocean, phytoplankton affect the absorption of sunlight in the upper ocean, and thus sea surface temperature.

Biogeochemical roles within the Earth System are numerous. Biota modulate atmospheric composition for a variety of constituents: atmospheric greenhouse gases such as carbon dioxide, methane, and nitrous oxide; aerosol precursors such as biomass burning and organic sulfur; and trace gases essential to the atmospheric oxidation state. Human emissions of CO_2 are the single largest component of present-day climate change and the contribution of CO_2 will grow over the next several decades, or longer, as CO_2 emissions increase with population and economic growth. At present only about half of anthropogenic carbon remains in the atmosphere to drive climate change; the remainder is removed in about equal amounts by the land biosphere and the oceans. The physical mechanisms governing the ocean carbon sink are relatively well understood, but the effectiveness of the future ocean sink is expected to decline due to warming and altered circulation. Models and some recent observations suggest that reduced CO_2 uptake may already be occurring in the Southern Ocean.

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. The paradigm captured in the present generation of models is that CO_2 fertilization enhances terrestrial plant productivity, offset by decreased productivity and increased soil carbon loss with warming and soil drying. This conceptual framework neglects nutrient effects, however. The availability of nitrogen, as well as other biogeochemical cycles, e.g., phosphorus, alters the magnitude, and possibly the sign, of the carbon cycle-climate feedback. Additional feedbacks associated with ozone deposition and methane emission will undoubtedly further alter the magnitude of the biogeochemical-climate feedbacks. Climate-carbon models indicate that the land carbon sink may be unstable under future climate change, leading to a potentially large positive feedback. On centennial timescales, climate change may alter the large-scale distribution of natural biomes over the planet, with significant impacts on carbon storage, surface albedo and the water cycle. 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 countered to an unknown extent by regrowth on abandoned farm and pastureland in the extratropics. The ambiguities in the mechanisms controlling the land carbon sink and their climate sensitivities translate into large uncertainties in future atmospheric CO_2 trajectories and climate change rates; uncertainties that need to be resolved to support carbon mitigation policies.

b) Decadal Climate Projections and Forecasts

Today, there is tremendous societal, as well as scientific, interest in how climate will change over the next several decades. In response, the CESM is moving forward to execute decadal climate projections and forecasts. A list of these projections and forecasts for the 5th Assessment Report of the IPCC has now been assembled. They include a series of 10 year hindcasts and prediction ensembles, some of which are extended for 30 years, including forecasts from 2006 to 2035. Such regional scale simulations will require an ensemble of at least ten runs using finer resolution components, and with the inclusion of simple chemistry, aerosols, and dynamic vegetation modules.

One very interesting and extremely important question is: Does it make a significant difference if the CESM is initialized to the actual climate at the start of the run? Exactly how to initialize the CESM is a major challenge, and one that other climate groups around the world are wrestling with as well. At a minimum, it will require data assimilation into the ocean component, and possibly sea ice extent in the Arctic. Does the CCSM need to have the correct state of the tropical Pacific and ENSO, and the North Atlantic meridional overturning circulation in order to produce a realistic decadal forecast for 2006-2035? There are many other data assimilation issues; for instance how to initialize all the model components around the modes of coupled variability intrinsic to the model.

There are some advantages to these decadal projections and forecasts. First, they are relatively short, so the atmosphere and land components can be run at higher resolution than previously used for IPCC scenario runs. An initial run using half degree resolution in the atmosphere and land components of the CCSM has shown that the sea surface temperature errors in the upwelling regions off the west coasts of North and South America, and off the west coast of Southern Africa are reduced by more than 50% compared to a comparable run using two degree resolution in the atmosphere and land, see Gent et al. (2009). Second, most of the climate change signal is already committed up until 2035, so these forecasts are much less dependent on the uncertainty in future forcing scenarios used to drive them than the traditional longer runs going out to 2100. The rationale for these decadal projections and forecasts is to produce regional climate information for the near future that is more relevant to decision makers.

There are many scientific questions to be addressed and answered better than previously:

1. The runs with and without data assimilation could be used to address the predictability of the climate system on decadal timescales. Also, the evolution of model systematic errors on shorter timescales might give insight into the mechanisms associated with these errors.

2. The decadal projections are a stimulus for a variety of multi-scale modeling activities, such as very high resolution one-way downscaling over the U.S.A. This could be used to examine implications for hydrology and water supplies, such as snow pack and runoff in the west, which is controlled by local mountainous topography.

3. Changes in extremes, such as extended heat waves, floods, droughts and in Atlantic hurricane frequency and intensity can be examined in these runs.

4. With the atmospheric chemistry component included, there will be simulations of the future air pollution, such as aerosols and ozone, in major urban areas and mega-cities.

5. Higher land resolution would also permit simulation of different classes of permafrost, and their different susceptibilities to, and interactions with, future climate change.

6. This type of decadal projection would emphasize human-induced changes in land use, because the dynamic vegetation module in the CESM land component would be active.

c) 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. Aerosols also act as cloud condensation and ice nuclei and regulate cloud properties, which strongly alter the short-wave and long-wave radiation budgets of Earth. Increased numbers of cloud condensation nuclei can 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. Increased numbers of ice nuclei can accelerate precipitation from clouds, reducing the cloud liquid water content and lifetime. In addition, absorption of solar radiation by aerosol particles in clouds can reduce the relative humidity and evaporate cloud water. All of these changes lead to changes in the cloud's radiative effects on the Earth's energy budget. Quantifying the anthropogenic aerosol impact on climate is important for isolating human impacts on climate change from natural variability.

The aerosol lifecycle is influenced by climate in several important ways. Emissions of carbonaceous particles from fires change as the climate changes. Emissions of aerosol precursor gases, such as dimethyl sulfate from the ocean and volatile organic carbon from trees, also depend on climate change. Climate-induced changes in the hydrologic cycle can affect aqueous-phase chemical production of sulfate, gas phase photolytic reactions, and removal of aerosol from the atmosphere by precipitation. Deposition of aerosol particles to the surface can reduce the albedo of snow and ice, thereby accelerating snowmelt and icemelt and further reducing the surface and planetary albedo. Deposition of nutrients in particles can enhance the productivity of the land and ocean, and hence influence the carbon cycle, while deposition of acids can reduce the productivity. Emissions of anthropogenic aerosol particles and aerosol precursor gases change as human activities change. Changes in energy technology change emissions of sulfur dioxide. Changes in land use change emissions of carbonaceous aerosol and soil dust.

It is clear that aerosols provide an effective link among a number of components of the Earth's climate system, where they connect the physical, chemical, biogeochemical and human components of the system. Representing all of these interactions requires a size-resolved and speciated representation of the aerosol. All major aerosol components (as a minimum, sulfate, sea salt, dust, organic carbon, black carbon), both natural and anthropogenic, must be treated. A comprehensive representation of the aerosol would be too expensive for many CESM applications, but the modal aerosol model developed for CCSM4 provides a framework that satisfies many of these requirements. The number, as well as mass, of each of three modes is predicted, with multiple components internally mixed within each mode. Parameterizations of all important aerosol processes are included, although the treatment of some processes, new particle formation, formation of secondary organic aerosol, are highly uncertain. Extensions to speciate dust are needed for applications to ice crystal nucleation and ocean fertilization.

d) Interaction of Chemistry and Climate

Changes in the distribution of large population centers are expected to occur over the next decades, with more megacities (population over 10 million) present in developing countries. These represent large "point" sources of pollutant that will lead to significant regional pollution degradation and possibly impacts on regional meteorology and climate. Some of those issues will be tackled under the IPCC AR5 decadal prediction experiments. Beyond those pioneering exercises, this type of regional problem will be particularly suited to an interaction between global and regional chemistry-climate models.

Through the newly developed capability of representing size distribution of aerosols, using the newly implemented modal scheme, CESM is now in position to explore in a more realistic fashion interactions between clouds and aerosols. While many studies can be performed in this framework, there is evidence that the chemical composition of aerosols is a critical element in their ability to act as cloud condensation nuclei. Better representation of the chemistry happening at the surface and inside the aerosols will be needed to ensure the correct representation of the water uptake of aerosols. To benefit from field experiments, this research area will require an ability of the model to perform simulations at high resolution and with large numbers of chemical constituents, thereby extending the on-going research in regional chemistry modeling.

There is increasing evidence that recent changes in atmospheric composition (especially of ozone) have lead to significant perturbations to the temperature distribution. As a corollary, trends in upper-tropospheric and lower-stratospheric climate (width of the tropopause, position of the zonal jets) have been observed, with potential impact on the position of the ITCZ and associated precipitation. The important question is to identify the specific roles of chemistry (through changes in emissions for example) and climate in explaining those trends. This is only one example in a large number of potential studies of interaction between climate (troposphere and stratosphere) and atmospheric composition, especially in relation to IPCC AR5.

Beyond the potential role of CO_2 on vegetation growth, pollution (mostly through ozone and nitrogen deposition) can lead to significant degradation of the ability of plants to grow. This type of problem requires a sizeable increase in the complexity in the representation of the interaction between plants (leaf uptake) and atmospheric chemistry; among other things, this could require a representation of chemistry in the canopy. In addition, recent field studies have highlighted the possible limitation of biogenic emissions (isoprene and monoterpenes) by CO_2, with the overall result of a decrease of the impact of temperature in a high CO_2 world. This can then be extrapolated to the cold climate of the Last Glacial Maximum where biogenic emissions would then increase. This has large implications on the tropospheric OH budget and methane lifetimes.

The Polar Regions are experiencing very significant modifications to their sea-ice distribution, especially in the Northern Hemisphere. Widespread surface (and lower troposphere) ozone depletion episodes (related to halogen chemistry similar to the one occurring in the stratosphere) are observed every winter and spring; these phenomena are not yet fully understood, but there is evidence that they happen through chemistry in the changing snow/ice surface. This halogen chemistry (bromine, chlorine and iodine) is actually present over most of the globe, and needs to be studied more as it reveals interactions between ozone and biogenic (planktonic) emissions from the ocean.

e) Role of the Middle Atmosphere in Climate

The role of the middle atmosphere in climate change is currently an open question. Changes in the propagation characteristics of planetary waves in the stratosphere appear to play a role both in stratospheric climate, via dynamical and chemical interactions that affect ozone concentration, and in tropospheric climate by influencing phenomena such as the Arctic and Antarctic

Oscillations (Thompson et al., 2005; Gillett and Thompson, 2003; Baldwin and Dunkerton, 2001; Son et al., 2008). The dynamics of the stratosphere are dominated by the interaction of dynamical forcing due to waves propagating upward from the troposphere and radiative forcing by solar heating due to ozone. Upward-propagating planetary waves affect the stratosphere directly. Small-scale gravity waves can deposit momentum in the stratosphere itself, or in the mesosphere, where they affect the stratosphere through "downward control." In order to understand the climate role of the stratosphere, it is necessary to model the coupled variability of dynamics and ozone.

The expected cooling in the stratosphere due to increasing CO_2 concentrations in the atmosphere is much larger than the expected increase in surface and tropospheric temperatures. This follows from the fundamental physics of radiative transfer, and is independent of the model used or the magnitude of water vapor feedbacks. 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. Of course, changes in chemical species that affect ozone chemistry also influence stratospheric climate, as noted above. Conventional climate models do not resolve the stratosphere adequately, and do not include feedbacks between ozone and dynamics; a deficiency that needs to be corrected.

Several studies have hypothesized that climate variability over the last several centuries is correlated with long-term variations in solar irradiance. There has also been considerable discussion of observed correlations between the 11-year solar cycle and tropospheric temperature and geopotential. However, the total solar irradiance variations do not appear to be large enough to force the observed climate variability in existing models. The radiative transfer codes in current climate models generally do not include wavelengths shorter than 200 nm, because these are almost entirely absorbed above the top boundary of these models. Nevertheless, solar irradiance variations at shorter wavelengths may influence the troposphere and surface climate indirectly, through changes in the stratospheric ozone distribution and circulation. Addressing this question requires models that extend through the mesosphere and include interactions among ultra-violet radiation, ozone chemistry and dynamics (Thompson and Solomon, 2002).

Research on the role of the middle atmosphere in climate and the effects of solar variability at short wavelengths requires a model that extends from the surface through the mesosphere, including interactive ozone chemistry. These requirements are among the goals of the Whole Atmosphere Community Climate Model (WACCM) project, which is motivated by an appreciation of the importance of coupling between different atmospheric regions, and the necessity of studying dynamical and chemical processes interactively and comprehensively. WACCM is built upon the software framework of CESM, in order to benefit from the development of the atmospheric component of the CESM, and the diagnostic infrastructure that exists for that model. However, there are specific needs that are crucial for successful coupling of the troposphere with the middle atmosphere that place constraints on the performance of the atmospheric component of CESM. One example is the requirement that the tropical tropopause in the atmosphere not be too cold compared to observations.

f) Role of Ice Sheets, Sea Ice and Land in 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, smaller abrupt changes have been identified during interglacial times as well, so mechanisms in the absence of ice sheets also must 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 understand better 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

g) Bounding Future Climate Scenarios

The best estimate from observations is that over the past 20 years, about half the rise in global sea level has been due to the thermal expansion of the ocean and half due to the increase in ocean volume because of melting land glaciers and ice caps. However, there are growing concerns that both the Greenland and West Antarctic ice sheets are beginning to melt more quickly as the Earth's climate warms (Shepherd and Wingham, 2007). There is evidence that the Greenland ice cap is melting considerably more than it is accumulating over the current decade (Steffen et al. 2004; Hanna et al. 2008). Also over the last decade, several small ice shelves have collapsed in both Greenland and Antarctica. Observations show that the glaciers behind these ice shelves are now flowing much faster than before (Joughin et al. 2003; Scambos et al. 2004; Rignot and Kanagaratnam 2006), which is also increasing the flow of fresh water into the global ocean. It has been suggested that, if the Earth's temperature warms by more than 3°C, then the Greenland ice sheet will become unstable, and will completely melt over the next few centuries. It has also been suggested that this process will be irreversible, even if the Earth's temperature subsequently cools. Total melting of the Greenland ice sheet will increase the global sea level by nearly 7 meters.

The projections of future sea level rise over the 21st century in the IPCC 4th Assessment Report did not take into account the possible increase in melting rates of the Greenland and Antarctic ice sheets. The reason was that the range of melting rate increase was not well bounded, but this implies that the AR4 estimate of sea level rise is almost certainly an underestimate. The CESM project plans to produce a more realistic estimate of the possible sea level rise over the 21st century. To do this, a land ice sheet component is presently being incorporated into the CESM framework. This work is being led by William Lipscomb of the Los Alamos National

Laboratory, with some colleagues from around the US University community. The first version will allow estimates of the future melting rate of the Greenland ice sheet, which affects both sea level rise and the ocean circulation. Additional fresh water deposited into the high-latitude North Atlantic Ocean may further slow down the meridional overturning circulation in the future. Subsequent enhanced versions of the new land ice component will model the interaction between ice shelves and the ocean, and the subsequent acceleration of glaciers behind the ice shelves.

Another possible large positive feedback to the Earth's climate system will occur if the future warming instigates a significant increase in the amount of methane emissions from the northern high-latitudes as Arctic permafrost thaws. Methane is about 25 times more effective as a greenhouse gas than carbon dioxide. It is rather difficult to estimate how much methane emissions might increase. However, there is some concern that it is already happening with observations indicating potentially widespread permafrost warming and thawing, and more limited evidence of associated methane release in parts of Arctic Canada and Siberia. Initial efforts to augment the CESM to address the issue of future northern high-latitude methane emissions have focused on improving the representation of permafrost dynamics (Lawrence et al., 2008). Work is underway to include a global natural methane emissions module, and a dynamic global wetland module into the CESM land component. This will enable the CESM to assess how northern, and global, methane emissions will respond to various climate forcings, and to bound the possibly serious impact of this effect over the 21st century.

h) Simulating Paleoclimates

Studying past climates provides a powerful resource for improving our understanding of the forcings and feedbacks that determine the state of the climate system on the time scale of centuries to millions of years. Paleoclimate simulations also act as means to integrate Earth as a system, because on these time scales physical, chemical, biogeochemical and ecological processes are integrally coupled. Thus, investigations of paleoclimate require the development of a comprehensive Earth System Model.

Studying past climates also provides valuable information on key processes that operate in warm climate regimes. It is estimated that by the end of this century Earth will experience a radiative forcing of somewhere between 5 to 10 Wm^{-2} due to increases in anthropogenic atmospheric carbon dioxide. Earth has not experienced this magnitude of greenhouse forcing for tens of millions of years. Thus, by simulating past warm climates, the CESM will gain a better understanding of the important Earth system processes that will operate throughout this century. Past climate records also provide evidence for abrupt transitions in the climate system. Paleoclimate simulations can provide important information on the possible mechanisms for such abrupt transitions. Thus, paleoclimate simulations provide a unique opportunity to provide essential information on the future of Earth’s climate.

One metric of success of a new paleoclimate CESM will be to predict the glacial-interglacial Earth system, including climate, ice, carbon cycle, chemistry, and ecosystem, forcing the model only with the insolation variations of the Milankovitch orbital cycles. A second metric of success will be the ability to define the sequence of processes that led to the great mass extinction events in Earth history.

The CESM is a very valuable tool for providing a global perspective for individual ice core measurements and to test hypotheses proposed to explain changes seen in paleoclimate records. Important scientific findings from current CCSM3 climate simulations include: latest Permian (~250 million years ago) simulations confirming the hypothesis that enhanced CO_2 greenhouse warming led to global ocean anoxia, and Last Interglacial (~130 thousand years ago) simulations indicating that Arctic warming comparable to projections over the next few centuries resulted in a smaller and steeper Greenland Ice Sheet.

i) Role of Ocean Mesoscale Eddies in Climate

The ocean interacts with other components of the climate system through the direct influence of sea surface temperature (SST) on the atmosphere, by transporting energy, water, and material around the globe, and by sequestering dissolved gases such as CO_2 in the interior out of contact with the atmosphere. Ocean mesoscale eddies and fronts play a role in each of these processes. The majority of the kinetic energy in the ocean exists at these scales, yet they are substantially smaller than can be explicitly resolved by the standard version of the CESM ocean component. A central problem in oceanography is to quantify the processes through which eddies and fronts influence the larger scale climate, and to represent these processes through parameterization in climate models.

While parameterizations of the effect of mesoscale eddies on the distribution of scalar properties continue to advance (e.g. Danabasoglu and Marshall, 2007), there remain significant gaps in our understanding, aspects that remain unrepresented, and biases in resulting property fluxes. Examples of processes that are not currently represented by mesoscale eddy parameterizations include: the interaction of eddies with inertia-gravity waves, the generation of recirculation gyres adjacent to western boundary currents (Nakano et al., 2008), and the forcing of zonal jet structures in the open ocean (Richards et al., 2006). Vertical motion in mesoscale eddies has also been shown to modify substantially primary productivity of oligotrophic marine ecosystems (McGillicuddy et al., 1998). Parameterizations that depict eddies exclusively as a mixing process cannot represent this nutrient transport mechanism.

Newly available high-resolution remote sensing products for ocean winds, SST, and surface currents have revealed a strong positive correlation between mesoscale SST variability and the surface wind field and heat flux out of the ocean; an indication that the ocean is forcing the atmosphere at these scales (Chelton et al., 2004). These frontal scale influences have been shown to extend out of the surface boundary layer into the troposphere (Minobe et al., 2008), providing a mechanism for scale interaction between the ocean mesoscale and the planetary scale atmospheric circulation. These effects are not represented in models that lack the resolution to explicitly resolve ocean SST fronts.

In order to improve our understanding of ocean mesoscale processes in the global climate, and to progress towards refining existing eddy parameterizations, will require a version of the CESM in which these oceanic scales are explicitly resolved. A suite of simulations in ocean-alone and fully coupled mode is needed to investigate the range of scientific questions outlined above. Recent simulations with basin-scale (Bryan et al., 2007) and global (Maltrud and McClean, 2005) ocean models suggest that a horizontal resolution of 10 km or less is necessary to adequately simulate both the intense western boundary currents and the mesoscale eddies. Prototype CESM experiments with a version of the ocean component configured similarly to the stand-alone ocean model used in (Maltrud and McClean 2005) have recently been carried out. In order to bring this model to the stage that long-term climate experiments are feasible, model developments in physical parameterizations and computational science are required.

Beyond a simple increase of resolution of the present model, CESM will need to continue to explore the sensitivity of eddy resolving solutions to subgrid-scale parameterizations. Despite the fact that mesoscale eddies will be explicitly resolved, adiabatic closure schemes may still be required (Roberts and Marshall, 1998). As yet, no practical scheme has been implemented. Significant interaction between mesoscale eddies and both interior and boundary layer diapycnal processes is expected. In particular, the energy cascade from the mesoscale to the submesocale remains unresolved, and will require further development of the eddy-mixed layer interaction parameterization currently used in the CESM ocean component at coarser resolutions (Fox-Kemper et al., 2009).

The increase in resolution from 100 km to 10 km represents an increase in computational cost of approximately 1000 over the current CCSM ocean component, and will require access to the very highest performance computational systems available. This requires that the model must scale to tens of thousands of processors. Efficient model execution on these systems demands highly scalable implementations of every phase of the code from local communication to global operations. Strong guidance from, and collaborations with, computational science researchers familiar with state-of-the-art computer architectures will be required.

j) Interaction with Integrated Assessment Modeling

The identification and evaluation of climate change response options, including both mitigation and adaptation, requires carrying out integrated analyses involving the physical climate system and the ecological and socio-economic systems with which it interacts. Stronger linkages between the CESM and the integrated assessment modeling (IAM) community offer a new means of bringing such integrated research to bear on pressing questions regarding possible responses to the challenge of climate change. IAMs link quantitative models of socioeconomic and biophysical components of climate change, and apply them to policy-relevant questions. Historically, IAMs have incorporated highly simplified representations of the climate system, and the interaction between the IAM and earth system modeling community has been limited. More recently, however, interest in exploring the potential of linking IAMs with earth system models has grown, stimulated in part by a new, IPCC-catalyzed scenario process that includes interactions between these communities, and will play a key role in generating integrated scenario analyses in the run-up to the IPCC Fifth Assessment Report.

Activities related to CESM that could promote interaction with the IAM community include a range of options, from incremental to ambitious, internal NCAR interactions to collaboration with the wider IAM community, and indirect exchanges to direct model coupling. Possibilities include:

Intensified interaction (e.g., through regular joint workshops) to ensure that IAMs produce inputs most useful to driving CESM simulations, and that CESM produces outputs most useful to IAMs and impact assessment researchers. First steps toward such interactions are occurring through the development of the Representative Concentration Pathways (RCPs) at the core of the new scenario process for AR5. Making CESM outputs more useful to IA could imply, for example, additional emphasis on statistical and conservative downscaling of physical model outputs, and/or high resolution simulations.

- Collaboration with IAM groups on joint research projects and assessments, in which questions arising from the IAM community can help prioritize CESM research directions and identify interesting scenarios to explore. A recent example is provided by a small internal NCAR project on “overshoot” scenarios, which play a key role in IAM analyses of achieving long-term climate change policy goals, and point to a need to assess how the climate system may respond to declining levels of radiative forcing.

- Develop a framework for linking IAMs to biophysical models of the land surface. Interactions at the land surface provide the most immediate interface between human activity and biophysical systems. However, linkage between IAMs and ESMs are difficult to make given differences in spatial scales, categories of land use and cover, ecosystem types, treatment of water systems, etc. A concerted effort could create a focal point within the U.S. for the integration of ecology, hydrology, biogeochemistry, and socioeconomic drivers of land use change into climate science. Such a framework would greatly facilitate the linkage of CESM to IAM models, and greatly improve the ability to conduct climate change impacts, adaptation, and mitigation research related to land use.

- Development of a framework for linking integrated assessment models with CESM more broadly. Such an effort would benefit from the computational resources and modeling expertise within CESM, and make it a leading project in linkages between physical modeling, integrated assessment modeling and quantitative assessment of the impacts of climate change. It would also provide a community modeling platform that was more useful to a wider range of users, including external IAM groups wanting to link their own model to CESM. For this reason, the activity should allow for a variety of different approaches and Integrated Assessment models.

6) Long-term Development of the CESM

a) Future High Resolution Atmospheric Components

In order to simulate more accurately the means and extremes of regional climate, future generations of CESM will have higher resolution atmospheric components, but their development will require significant changes in the numerical algorithms for the dynamics, the grid structure and, ultimately, in the dynamical formulation. When thinking of model resolution, it is necessary to distinguish resolution from grid spacing. With spectral models based on spherical harmonics, the resolution is defined by the wave number truncation with a transformed grid spacing that is typically 3-4 times smaller than the most highly resolved feature. Similarly, for finite difference and finite volume approaches, the resolution is typically a factor of four coarser than the grid resolution, as this is the smallest feature that can be simulated with fidelity by these methods. The current CAM4 production version uses a grid spacing of approximately 100 km, which results in an equivalent resolution for a spectral model of T85, although experimental versions are in use with resolutions two and four times greater.

Climate models benefit greatly from atmospheric general circulation model (GCM) development by the global numerical weather prediction (NWP) centers. In general, a state-of-the-science climate model is a factor of 3 to 10 behind current NWP models in terms of resolution because of the increased simulation times and the inclusion of processes that are important to climate, but are inconsequential to influence 10-day predictions. The global weather prediction model used today by the European Center for Medium Range Weather Forecasting (ECMWF) produces 10-day forecasts twice per day using a T799 spectral truncation. The ECMWF employs their very high resolution system to accurately simulate severe weather phenomena, such as localized intense rain or wind areas that are often embedded in larger weather systems, and circulations tied to small-scale terrain or coastlines. The global prediction skill of their model is also improved because the energy transfer among the smaller scales is better resolved. The next generations of CESM should strive for NWP resolution in climate simulations. In the longer term, research into cloud resolving global models, coupled with "Exascale" computing power is expected to lead to climate models that can explicitly resolve clouds and convection, while simultaneously satisfying the global energy and mass constraints to produce accurate climate simulations.

Developing modern climate and weather prediction models requires enormous human effort as many interacting physical processes need to be faithfully represented. Increasingly, we are making weather forecasts with climate models to more efficiently test its parameterizations. Conversely, we are making long simulations with weather prediction models for medium-range forecasting and regional climate modeling. Conceptually, climate and weather forecast models could use unified dynamics and physical parameterizations. This unified model paradigm is being effectively employed at ECMWF and United Kingdom Meteorological Office (UKMO), which now have two of the world's best-performing weather and climate models. The CAM development strategy should adopt this paradigm to the extent practical, while always acknowledging that priority is given to producing the best global climate simulations. An important first step is developing a global climate model with resolution comparable to the best global NWP models in use today, such as those at ECMWF and the UKMO. To the extent possible, CAM development should proceed in close collaboration with NWP modeling groups, particularly the Weather and Research Forecasting (WRF) community. For example, substantial cooperation is anticipated between CAM and WRF developers on evaluating formulations for global nonhydrostatic dynamical cores and grids for future generations of both models.

Development of future higher resolution versions must anticipate and integrate progress in numerical algorithms, programming models and computer architectures (see section 6h). Critical to successful development is an open and thorough testing of competing ideas for the next generations of high resolution atmospheric GCMs. For example, several alternative grids and numerical approaches were explored at the NCAR ASP 2008 Summer Colloquium on Numerical Techniques for Global Atmospheric Models. Although a number of model tests have been developed and applied over the years, CESM should define a priori a full testing hierarchy to guide the development stream (Jablonowski et al, 2008). In particular, the Held-Suarez, aqua-planet and full twenty-year AMIP tests should be applied, in order, with a complete evaluation of each to determine the acceptability of new dynamical cores, model formulations or grids. Furthermore, the model must maintain the mass and energy conservation constraints required to perform century and longer simulations.

CAM5 - 2012

A logical next step for CAM will be developing a next generation dynamical core using the existing hydrostatic model formulation on an isotropic grid, potentially with new algorithmic approach and numerical methods. The target resolution for the model would be close to the limits imposed by the hydrostatic formulation and the scale limits of sub-grid scale parameterizations, which is a grid spacing of approximately 10 km. Possible grids include, but are not limited to, the geodesic grid used by the CSU group and the German weather service, and the cubed-sphere grid used by Japanese groups and GFDL. Potential algorithmic options include the SEAM/HOMME spectral element dynamical core, an updated version of current FV dynamics, and improved spectral methods which are designed for distributed memory computers. An ambitious, but realistic goal will be to port current and future physical parameterizations to this new core running at the highest resolution.

CAM6 – 2015

Starting with the completion of CAM4, a longer-term roadmap should be developed for the development of CAM. A priority should be the exploration of non-hydrostatic formulations capable of global simulations with a grid spacing of approximately 1 km, which is required to accurately simulate atmospheric convection (Redelsperger and Sommeria, 1986). The difficulty in synchronizing the development of new model dynamics, modifications to the dynamical core and the evolving nature of computer hardware, with the concomitant changes to program models, should not be underestimated. While the development path of CAM5 will be relatively straightforward, the strategy for CAM6 will be less clear and will likely require mid-course corrections at 2-3 year intervals.

b) Future Ocean, Sea Ice, Land, and Land Ice Components

Solutions of ocean climate components in the non-eddy-resolving regime are still more dependent on the quality of the parameterizations used than on the details of the model numerics. However, future development certainly needs to be carried out on both aspects of the model. The recent Climate Project Team (CPT) work on eddy parameterization has resulted in a Gent/McWilliams coefficient that is a function of space and time. Further refinement of the coefficient is desirable and whether the eddies produce a diapycnal component of tracer mixing. It is also important to have an energetically closed formulation of the diapycnal mixing that includes the effects of tides, internal wave breaking, etc. in the deep ocean. The effects of submesoscale eddies is also in the current version, but needs further work which will still be relevant when the ocean component is run at eddy-resolving resolutions of 1/10° or finer. Over the next several years, more and more development work and runs will be done at this resolution, but there will still be the need for non-eddy-resolving versions for very long runs, and applications that need a large ensemble of runs. An early version of an overflow parameterization is also in the present ocean component. This needs to be evaluated and developed further, possibly in conjunction with a bottom boundary layer parameterization. Another possible new direction is to allow for the air-sea interaction to depend on properties of the surface wave field and when they break.

In terms of future model numerics development, the most fundamental would be to move to a model that uses density coordinates in the deep ocean below the strong mixing region. This would reflect the fact that most tracer transport and mixing is along density surfaces in the deep ocean. However, it is still advantageous to keep depth coordinates near the ocean surface. Work in this direction has occurred recently at Los Alamos, with development of a hybrid coordinate version of the POP model, called HYPOP. When this code is fully developed, then it needs to be implemented and evaluated in the coupled framework of the CESM. It should also be compared to the HYCOM ocean model developed by Chassignet and colleagues that also uses hybrid density/depth coordinates which has very recently been implemented in the CESM framework.

Further evaluation of transport schemes that have low dissipation and dispersion needs to continue. The schemes also need to be sign definite when used with the ocean ecosystem model for carbon cycle applications. In addition, fully-implicit time stepping schemes need to be evaluated with emphasis on how to set the necessary preconditioners. If implemented, such a scheme would strongly reduce the computer time needed for long runs, but would it give accurate solutions?

Future versions of the ocean component need to resolve the coastal regions much better than at present. This can be done either by a mesh refinement strategy or by a nested regional model, see Section 6g. There are several reasons for this additional coastal resolution, such as this is where the ocean interacts with the land component, is where much of the ocean's biogeochemistry and biota occur, and where much of the Arctic methane clathrates occur. Potential release of this methane is a very important question and will certainly result in an abrupt climate change if the release occurs with any rapidity at all. Resolving the ocean margins is also important if the CESM is to model the interaction between the ocean and ice shelves in the Arctic and Antarctic. Several small ice shelves have collapsed in the last decade, and the CESM needs to evaluate the potential for the collapse of much larger ice shelves, which could potentially cause a significant jump in the global ocean sea level.

Future development of the CESM sea ice component can also be divided into work on dynamics and numerics, plus work on new parameterizations. The dynamics work includes advances in the sea ice rheology to refine the current elastic-viscous-plastic formulation of Hunke and Dukowicz (2002). The current version of CICE used in CCSM4 is also somewhat sensitive to parameter choices in the ridging and rafting scheme, and further work is needed here, along with refinements to the transport scheme of Lipscomb and Hunke (2004).

In terms of new parameterizations, there are plans to improve the snow physics, sea ice hydrology, and grounded ice. The present snow physics is fairly simple, whereas in reality it is much more complex, with important consequences for both the snow albedo and ice formation as the snow ages. The sea ice hydrology is also very important for the snow albedo, as melt ponds formed during the spring reduce the albedo significantly, which is a positive feedback on the snow melting rate. Experience with the CESM has shown that, if the snow does not completely melt in the Arctic spring, then no surface sea ice melting occurs, and the permanent sea ice becomes much too thick. Sea ice does also play some part in the carbon cycle, and it can be significant in the polar regions where biological productivity is relatively small. In spring, quite large amounts of algae can form on the bottom of the sea ice. In addition, when sea ice melts the dust and iron it contained go into the ocean, which increases the productivity in the polar regions. New parameterizations for these processes are being developed that will be included in further development of the CESM carbon cycle in the future.

All versions of the CCSM to date have required the atmosphere and land components to run on the same horizontal grid. The capability for these two components to run on their own separate grids is presently being implemented, and there are two main reasons for this. The first is that it is anticipated that the atmosphere component will soon move to a non latitude/longitude grid, see Section 6a, whereas the land component will continue to use such a grid, and second this allows the land component to have a fine-mesh capability and use a resolution of 1/10°. This will allow a much better representation of orography and land cover, and result in improved albedo, hydrology, and river transport, for example. These are all important when the CESM will be used to make regional climate predictions for the USA over the next few decades, in order to answer questions such as the future of water resources in the western USA, and permafrost degradation in the Arctic. The increased land component resolution will also benefit the representation of the terrestrial carbon cycle by improved soil and vegetation control of the carbon budget and control of dust emissions by both natural droughts and human induced land cover changes.

New capability over the next several years in the land component will include the following. Close the nitrogen and methane cycles and represent the role of land disturbance on biogeochemical cycling. Further development of the total water cycle will include managed river and lake systems, irrigation, and the river transport of nutrients, chemicals, and sediments. Several human systems will also be included in future versions of the CESM land component. These include agricultural activities, such as crops, animal husbandry, a more sophisticated urban component, human fire systems, and human inputs on soils by use of nitrogen fertilizer, for example.

Observations over the past five years have shown that the Greenland ice sheet is losing mass with more melting than accumulation. In addition, observations in both Greenland and Antarctica show that glaciers have accelerated, especially when small ice shelves at their snouts have disintegrated. These observations have important consequences for future global sea level rise. In response, a small group of scientists, led by Bill Lipscomb of Los Alamos National Laboratory, decided that the CESM needed an ice sheet component. They chose the GLIMMER model developed by Tony Payne at the University of Bristol, see Payne (1999). Over 2008, it has been modified and developed to fit into the CESM framework as a separate component, but very closely tied to the land component. The simplified dynamics of GLIMMER is applicable to the Greenland ice sheet, and so the initial focus is to obtain a good representation of the present day mass balance and ice sheet thickness. Simulations of various paleo epochs will also help define the thermodynamic component of GLIMMER. The focus of this work is to run in 2010 some simulations of the 21st Century that include an active Greenland ice sheet for possible inclusion in the IPCC AR5 report. This will give projections of both the possible sea level rise due to the melting ice, and the effect of the melt water on the strength of the meridional overturning circulation in the North Atlantic Ocean.

In August 2008 a meeting was held at Los Alamos to organize interested scientists from across the USA to further develop the GLIMMER model into a next-generation community ice sheet model, just as the CESM project has done for its physical and carbon cycle components. This development will take a few years, but will produce a component that is able to represent the Antarctic ice sheet, as well as the Greenland ice sheet. The Antarctic ice sheet is more complicated because it has extensive ice shelves that strongly interact with the ocean, in addition to thermodynamic interaction with the atmosphere. This will require the component to include higher-order dynamics which controls glacier flow and variable resolution with unstructured horizontal grids that provide much finer resolution near the ice sheet boundaries. The new component will also require better hydrology parameterizations to represent all the effects of water on the ice sheet. Probably the most difficult aspect is how to model the ice sheet interaction with the ocean that controls how fast the ice sheets melt. This requires much higher resolution in the ocean component that must be provided either by the global model or by interaction with a nested regional ocean component. This is a very difficult problem that will take some time to complete. However, it is important that a future CESM be able to represent the future behavior of the climate system with interactions of both the Greenland and Antarctic ice sheets.

c) Future Biogeochemical and Ecosystem Components

Better understanding of the ecological and biogeochemical feedbacks with climate requires a significant expansion of current CSEM land and ocean model capabilities. Preliminary work in CSM 1 involved the addition of carbon-only land and ocean modules to the physical climate system (Doney et al., 2006); the CSM 1 coupled carbon-climate simulations highlighted many of the issues involved in transient response of the carbon cycle over the 20th and 21st century (Fung et al., 2005). Advances in CCSM 3 included the incorporation of a marine ecosystem model with nitrogen and iron cycling in the ocean. Terrestrial developments included pilot efforts on carbon-nitrogen dynamics, land-cover change, and dynamic vegetation. Ongoing and future work involves coupling of these separate development streams, improving parameterizations of agricultural and urban land, and evaluating model results more rigorously utilizing flux tower, process study and remote sensing data. Implementation of the full scope of nitrogen and phosphorus dynamics and methane and ozone feedbacks requires more sophisticated coupling between land biogenic emissions and atmospheric chemistry. Additional development of land surface parameterizations is also needed, e.g., models of the hydrology and biogeochemistry of wetlands and peatlands.

Land-atmosphere interactions in climate models must be expanded to represent biogeographical processes such as land use, fire, and post-disturbance vegetation succession. A major focus within the CESM project will be the development of the modeling tools and validation datasets for incorporating and assessing historical and future land use; the dynamics of managed forest, rangeland, and agricultural systems; and deliberate land management strategies to mitigate climate change. On an even longer timescale, pilot efforts should begin with integrating natural and social science research with respect to land use, as well as trace gas emissions.

On the atmospheric chemistry side, developmental paths underway will need to be augmented. First, prognostic dust emission, transport, and deposition are being included in the CESM 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, which is driven to a significant extent by biogeochemical trace gas fluxes from the ocean and land.

Ocean-only experiments have been conducted to assess the effects of atmospheric iron deposition on ocean biological productivity, carbon sequestration, and nitrogen fixation and denitrification. Next steps will involve coupling the atmosphere-land-ocean iron cycle including terrestrial dust production, which is sensitive to vegetation, land-use and water cycle, and more sophisticated iron sources from continental margins. The coastal shelves and continental margins are hot spots of marine biological productivity, fisheries and biogeochemical transformations. Present versions of the CESM do not resolve coastal dynamics well, however, and future improvements will likely depend upon regional nesting within the ocean/atmosphere system.

In the present CESM, 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. Several new modeling activities will be needed 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 occur in estuaries; high resolution modeling of coupled coastal ocean dynamics; and a dynamic marine sediment-water column module.

d) Future Aerosol and Chemistry Components

The modal aerosol model provides a computationally efficient framework for representing aerosol properties in the CESM, but improvements are needed for several processes. First, to reduce the anthropogenic aerosol indirect effect new sources of natural aerosol need to be added, including primary and secondary marine organic aerosol. Second, emissions of mineral dust need to be speciated to distinguish between components with different optical properties, different microphysical properties, and nutrients important for fertilizing ocean biology. Third, the size distributions of emissions of primary particles, particularly those arising from combustion, needs to be constrained better with field measurements. Fourth, emerging advances in the treatment of new particle formation should be implemented. Fifth, new understanding and proposed mechanisms of formation of secondary organic aerosol should be applied. Sixth, recent more accurate and computationally efficient treatments of aerosol thermodynamics and water uptake should be considered. Seventh, effects of aerosol on shallow cumulus clouds should be added to the shallow cumulus scheme, and new treatments of the effects of aerosol on ice clouds should be considered. Finally, an alternate method of representing the aerosol moments should be introduced.

One interesting and challenging topic for Earth System Models is the possibility of fully coupling atmospheric chemistry with the global biogeochemical cycles of key species. This coupling would include coupling of the i) the nitrogen cycle; ii) the carbon cycle; iii) the sulfur cycle and iv) the chlorine and bromine cycles between the land, ocean and atmosphere. The complex nitrogen cascade which occurs after the introduction of reactive nitrogen into the environment involves not only many species, but the interaction of all components of the earth's surface (snow, land, water) with the atmosphere. The increase of environmental reactive nitrogen over the 20th century is largely linked to agriculture. However, the critical nitrogen transformations that occur locally within the soil are communicated to the atmosphere where they play a critical role in regulating the concentration of greenhouse gases including nitrous oxide and ozone. The terrestrial carbon cycle is impacted by atmospheric nitrogen deposition and ozone. It is directly linked to the atmosphere through the emission of methane and biogenic species. The resulting emissions are sensitive to climate change through changes in wetland distribution and changes in temperature and CO_2. In turn, they impact climate by regulating the concentration of the greenhouse gas methane as well as atmospheric aerosols. Likewise sulfur (as DMS) and chlorine and bromine (as halogens) emissions from the ocean are an additional link between atmospheric chemistry, climate and global biogeochemical cycles.

Additional challenges include an improved representation of the dynamical and chemical coupling between the stratosphere and the troposphere in Earth System Models, as well as an improved representation of megacities. Urban emissions are expected to change significantly over the next century due to an increased number of megacities, especially in the tropical regions. While models are significantly improving in their horizontal resolution, we envision developing a representation of chemistry within the Community Land Model such that the nonlinearities in the chemistry can be represented at the size of the CLM grid, then distributed to the atmosphere. This would enable a much improved representation of urban chemistry, and its impact on the large-scale chemistry and climate. An important aspect of this would be improved representations of the interactions between gas-phase chemistry and aerosols whose representation is currently either simplified or not included in the CESM. Examples include the production of secondary organic aerosol precursors, sulfate, nitrate, and ammonia by chemistry, and the effect of aerosols on photolysis and heterogeneous surface reactions.

e) Future WACCM Component

Long-term development of WACCM will lead to advances in both the dynamical and physical components of the model. The way WACCM parameterizes gravity waves will be improved in two areas: momentum conservation at the source and top of the model; and the thermal effects of dissipating waves (diffusion, thermalization of wave energy) will be re-evaluated and refined by comparison with observations. Modifications will be carried out with the goal of internally generating a quasi-biennial oscillation (QBO) within WACCM. Necessary changes will likely include the following: (a) fine (sub-kilometer) vertical resolution; (b) highly scale-selective hyperdiffusion; and (c) a convective heating parameterization that produces large variability at time scales from 10 days to a day or less.

Now that CAM-CHEM and WACCM utilize the same code base, the chemical solver and method of specifying a chemical reaction scheme are identical between the models. Further chemistry package development is planned with the goal of unifying the chemical codes across CAM-CHEM/WACCM and WRF-CHEM. It is also planned to unify photolysis and heating calculations within these models; currently these are independent calculations. For particulate and cloud studies in the lower, middle and upper atmosphere, a sectional microphysical model (CARMA) will be incorporated into WACCM. Simulations using this model will aid in further development of microphysical parameterizations in WACCM.

Development plans for WACCM-X (a version with model top at ~500 km) include development of modules that resolve ion and electron transport, ambipolar diffusion, and include an ionospheric dynamo. Modification of the dynamical core will be necessary to simulate horizontal molecular diffusion and ion transport. There are also plans to couple WACCM-X with a plasmasphere model (the Global Ionosphere and Plasmasphere), and a magnetosphere model (the Lyons-Fedder-Mobarry model).

f) Future Paleoclimate Developments

The success of a vibrant paleoclimate program within the CESM depends on achievement of the following developments:

The development and maintenance of a low-resolution version of CESM. The paleo record demonstrates rapid and dramatic changes in ocean circulation and climate on timescales from decades to tens of thousands of years. To understand the mechanisms that determined the state of the past Earth requires the capability of running a matrix of simulations with CESM for thousands to tens of thousands of years. The attribution of natural variability and forcings in defining past climate sensitivity requires a systematic experimental design that can only be accomplished with a hierarchy of models of varying complexity. It is essential that the CESM project retain as a high priority the development and maintenance of low-resolution versions of the CESM.

The incorporation of paleotracers within CESM. Past climate changes are recorded in ice cores and ocean sediments using tracers that are not currently simulated within the component models of CESM. In order to gain an understanding of whether the CESM is able to replicate such changes, it is essential to be able to simulate the tracers that are recorded in the observational record. The first paleotracers to be incorporated into the model should be $\delta^{18}O$ (used for assessing atmospheric temperature, precipitation, and ice-volume changes from water isotopes in polar and tropical ice cores); radiocarbon (which yields information on changes in rates of ocean ventilation); and $\delta^{13}C$ (which has been widely used to infer dramatic shifts and re-organizations in ocean circulation).

Development of the capability for CESM to simulate past ice sheets. The GLIMMER and CISM ice sheet models currently being developed by the new land ice working group concentrate on the stability of the Greenland and Antarctic Ice Sheets. Understanding the dynamics of past climates requires the development of a framework that includes other land-based ice sheets, and incorporates the response of the bed to changing ice load of isostatic rebound.

Further development of the marine and terrestrial biogeochemistry in CESM. The quantitative and mechanistic explanation of atmospheric carbon dioxide variations over the glacial-interglacial cycles of the last million years remains one of the major unsolved questions in climate research. Simplified models suggest that no single mechanism can be invoked, but rather that physical and biogeochemistry changes in the ocean and over land need to be considered and that the relative importance varies as the climate state changes. To fully assess the processes responsible for past variations will require inclusion of new features to the biogeochemistry modules, for example, coral reef regrowth and an ocean sediment model.

Development of a framework to model atmospheric chemical state of past Earth. Atmospheric chemistry simulations for the latest Permian indicated that release of H_2S led to an increased methane lifetime, which would have caused a collapse of the ozone layer. Hydrogen sulfide in high concentrations is directly toxic to many life forms. A frontier for CESM is to investigate the interaction of physical and chemical processes for the habitability of Earth.

g) Nested Regional Climate Models

The climate research community is beginning to use higher resolution (~50 km) models for the decadal prediction problem, but global modeling frameworks that resolve mesoscale processes are needed to improve our understanding of the multi-scale interactions in the coupled system, identify those of greatest importance, and document their effects on climate. Ultimately, such basic research will help determine how to better represent small-scale processes in relatively coarse resolution Earth System Models (ESMs). The impact of small-scale processes on larger scales is often termed “upscaling”.

There is a wide range of upscale interactions to be considered. Current parameterization schemes do not adequately handle the mesoscale organization of convection, which is a critical missing link in the scale interaction process. The limited representation of convection and cloud processes is likely a major factor in the inadequate simulation of tropical oscillations. Cloud and convective processes also appear to play a role in the well known double Inter-Tropical Convergence Zone (ITCZ) bias issue, though coupled processes involving a systematically intense equatorial cold tongue in the ocean also likely contribute to this persistent systematic error in many coupled models.

Uncertainty in the representation of clouds (on all scales) is also a major influence in the response of the climate system to changes in radiative forcing. Improved simulation of cloud processes in the Multi-scale Modeling Framework (MMF), which embeds two-dimensional cloud resolving physics within three-dimensional weather scale physics, has shown improved MJO variability and reduced the bias in Kelvin wave propagation.

Another scale interaction problem is the challenge in modeling the Subtropical Eastern Boundary (STEB) regimes off the coasts of Southwest Africa, Peru-Ecuador-Chile, and Baja-Southern California. These regimes are marked by marine stratus, equatorward alongshore winds, and ocean upwelling. Large and Danabasoglu (2006) suggest that better resolution of these features produce not only a better simulation of the regional climate, but also effects that propagate and strongly influence the large-scale climate system, reducing rainfall biases across the tropical oceans.

Other examples of “hot spots” with significant upscaled effects include the monsoon regions of India and Tibet and Central and South America where steep topographical gradients and mesoscale processes such as low-level jets and mesoscale convective complexes play an important role in the water and energy budgets locally and remotely. Over the Maritime Continent, Lorenz and Jacob (2005) presented a study of two-way coupling using global and regional models, and demonstrated large and positive impacts on the tropospheric temperature and large scale circulation in the global climate simulation.

Clearly, addressing these errors is critical to climate prediction on all time scales. Therefore, there is a strong need to develop pilot projects to demonstrate the methodologies and impacts of multi-scale interactions on the regional and global climate. While numerical models and techniques will be central to this effort, so too will be sophisticated theoretical and physical research to both understand and specify the critical interactions.

One pilot project that has been developed is the “Prediction Across Scales” initiative at NCAR. This initiative is a collaborative effort between CGD, MMM and interested participants from the broader (CCSM and WRF) community to coordinate research and system development activities across weather and climate scales. Recent major advances in petascale computing, coupled with rapid advances in scientific understanding, are enabling progress in simulating a wide range of physical and dynamical phenomena with associated physical, biological and chemical feedbacks that collectively cross the traditional weather-climate divide. Such simulations and predictions are essential to a society that is becoming much more sophisticated in its requirements for weather, air quality and climate predictions and that is able to make useful economic and social use of such improvements. Moreover, as discussed above, fundamental barriers to advancing such prediction on time scales from days to years, as well as long-standing systematic errors in weather and climate models, are partly attributable to our limited understanding and capability to simulate the complex, multiscale interactions intrinsic to atmospheric and oceanic fluid motions.

The enabling tool for this type of research will be the Nested Regional Climate Model (NRCM). The result of this ambitious effort to combine high resolution regional atmosphere and ocean models with a state-of-the-science climate model will be fundamental progress on the understanding and prediction of regional climate variability and change. In particular, embedding the WRF and a Regional Ocean Model System (ROMS) within CESM will allow scientists to resolve processes that occur at the regional scale, as well as the influence of those processes on the large-scale climate, thereby improving the fidelity of climate change simulations and their utility for local and regional planning. More information on NRCM, including existing and planned numerical experiments, can be found at www.nrcm.ucar.edu

h) Algorithms and Computational Environment

Future generations of Earth System Models will face significant algorithmic and computational challenges. The present petascale computers consist of hundreds of thousands processing elements with a complex memory hierarchy. We expect that the next generation exascale machines will have factors of 100s more processing elements requiring millions of parallel threads of execution. Computer chip manufacturers have abandoned the increase in clock rates and now rely on adding ever more cores to improve performance, challenging application programmers to identify finer grain parallelism and manage deeper memory hierarchies for efficient computation. Since these platforms may arrive as early as 2015, new approaches and paradigms will need rapid development in order to take advantage of the science opportunity presented by this computational power.

Scalability will be a critical requirement of every component in the next generation Earth System Model. The biggest scalability bottleneck in today's Earth System Models is the atmospheric dynamical core. This bottleneck is created by the pole problem introduced by the use of latitude/longitude grids. New dynamical cores with cubed sphere and icosahedral grids, along with yin-yang (baseball) and other overlapping systems, show promise for scalability in highly resolved models. In addition, new coupling mathematics algorithms will also be required. To develop the ability to predict future sea level rise, ocean circulation and to understand the effects of climate change on extreme events, new components will be added to the model. New physics and many new scales will also be introduced, and thus require research into the best multi-physics and multi-scale coupling strategies. The human dimensions of climate change will also begin to be more closely integrated with the physical models for sustainability studies and consistency with decision support and integrated assessment modeling. All new techniques will need to be developed from inception with *scalability* as a key requirement. In addition, the time it takes for model developers to incorporate and evaluate new components will need to be dramatically reduced, thereby also requiring the need for research into improved verification and validation strategies and an investment in associated software engineering support.

Another critical computational challenge for the next Earth System Model will be to determine the optimal programming model for the anticipated new computing architectures. The requirement that models run efficiently on processors with many more cores than they have today, but with little increase in the processor's memory bandwidth, jeopardizes current programming practices. In the current petascale environment where the number of cores per socket is relatively small, we expect that the hybrid MPI and OpenMP paradigm will be adequate (Drake, et al. 2008). However, as we move towards scenarios where we expect applications to run on systems with millions of cores and diverse architectures, it is doubtful that this will continue to be the case. These new architectures will need to be programmed with techniques exposing finer grain parallelism and where computation is coordinated with the memory hierarchy. Scalability and reproducibility will also be key requirements. The current programming models (MPI+Fortran) and fault tolerance approaches are not scalable, and the likelihood of undetectable errors will increase without new improvements to fault detection and better resilience strategies. In addition, computer vendors are also considering embedded processor technology that could permit multiple systems to be built, each specialized to a particular class of problems in order to address the cost and power barriers faced by conventional approaches. If these approaches can be successfully applied to resolving climate modeling computational bottlenecks, then the climate science community will face even greater programming challenges. Finally, fault resilience and auto-tuning will be needed in order to enable better throughput and efficient utilization of hardware resources. Such a new programming infrastructure is required in order to enable sustained performance on upcoming systems. Without this, we may fail to meet the performance requirements necessary to achieve the desired science impacts. Since there are many options for programming models in the 5-10 year time frame, and code conversion would take nearly as long, an experimental approach to prototype parts of the model should be pursued.

Practical simulations for decadal prediction and ensemble runs will also require revisiting the software architecture and ensuring effective parallel I/O that achieve rates of 100's of GBs. Due to the many requirements on the I/O subsystems of these models, a more flexible utility structure is needed that is supported and available across centers and hardware and software vendors. This issue will only be aggravated by the use of unstructured grids or by the selective output of extreme events. Improving I/O performance will also be necessary in order to support the dramatic increase in data generated by ensembles of long time simulations required for studying extreme events and by those needed for decadal predictability efforts. The shortest term goal within the next 5 years is to develop new parallel I/O systems at all levels.

As Earth System Models become increasingly complex and high performance computing architectures change faster than ever, CESM will need to work with the modeling community to develop programming models and auto-tuning technologies (as a risk mitigation strategy) for the next generation Earth System Model that offer performance portability and fault resilience. A concerted effort to prototype key climate algorithms to understand the relative merits of alternative programming technologies will need to be a high priority. Obtaining reasonable performance on multi-core platforms will require better performance introspection to do auto-tuning, and a better understanding of causality with sufficient coverage by instrumentation, to understand performance. A programming model is necessary, but not sufficient. Scaling to millions of processing cores will also require parallel scalability in *every* aspect of the climate model. The end result of both of these efforts will be to enable simulations with the most complex Earth System Models that will effectively utilize exascale class systems.

7) Resources Needed to Accomplish the CESM Goals

Resource needs can be divided into two categories: people and computer resources. Resources for scientists and software engineers have diminished over the years 2004-2008. The consequent reduction in people working on the project meant that progress has been slowed down. New knowledge and developments have not been incorporated into the model rapidly enough. There were too few people to modify and run the models for development, scientific exploration, and assessment-type production runs. This led to a rationing of resources determined by program priorities. IPCC-type runs, done as part of the CCSP commitment to the IPCC assessments, while a critical part of the process and method of model evaluation, have nonetheless come at the expense of model development and research. This science plan calls for strongly enhancing the human resources needed to avoid this rationing in the future. Better links between the process research and parameterization programs are needed in order to move their developments more rapidly into the core model. Further, if the enhancement is large enough, it will be used to connect with the consumers of simulation output, such as the Integrated Assessment and

Ecological Impacts communities, to give them much easier access to CESM data. However, the envisioned enhancement requires a substantial investment in both scientists and software engineers to make the strong connections between the process research, the models and users of climate model output. This will allow NCAR, DOE laboratories and University collaborators to leverage the investments in computational science and information technologies made by the DOE Office of Science and the NSF across all the fields of science it supports. As this plan was being finalized in early 2009, there are hopeful signs that the budget of the CESM project will have a reasonable increase in FY10.

The second category is computing resources, which, in contrast to human resources, have increased significantly over the past five years. This has enabled the CCSM project to contribute to the AR 4, and subsequently develop the CCSM 4. However, frequently testing and development of the next generation of model components are delayed to meet the near term production needs for future scenario projections. This "either/or" situation is not healthy. Climate modelers need a range of resources, from desktop to leadership-class computing capabilities, data management and archive centers and the people to manage them. The CESM project requires dedicated, large capacity resources from the DOE leadership-class centers at several of their laboratories, the Climate Simulation Laboratory run by NCAR, and, in addition, the NSF Tier I computational centers, with appropriate human and data storage support around them to optimize their benefit for climate modeling.

8) Products

An Earth System Model framework that can be used for basic science research, future climate projections, and decadal forecasts. Model versions will be formally released when appropriate, which is at least every few years and probably timed to synchronize with the IPCC assessment report schedule. Model code that is freely available from the CESM web site, and free access to the output from the suite of runs performed for IPCC reports.

A system of working groups that allows any interested scientist to become involved in the project, so that ideas can be evaluated and incorporated into the model. Meetings of these working groups and the annual workshop are forums where students can be trained in the science of climate modeling and analysis of the model output and observations.

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