CESM

Community Earth System Model

Proposal for CSL Resources

Period of Performance: 4/1/11 – 6/30/12

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Introduction

NCAR has a proud and unique tradition of collaboration with scientists from universities, national laboratories, and other research organizations to develop, continuously improve and support the scientific use of a comprehensive Earth modeling system that is at the forefront of international efforts to understand and predict the behavior of Earth's climate. For many years this tradition has been realized through the development and application of the Community Climate System Model (CCSM), in large part through its access to and use of the Climate Simulation Laboratory (CSL) computing facilities. CCSM output, for instance, has been used in many hundreds of peer-reviewed studies to better understand the processes and mechanisms responsible for climate variability and climate change. In addition, simulations performed with CCSM have made a significant contribution to both national and international assessments of climate, including those of the Intergovernmental Panel on Climate Change (IPCC) and the U.S. Global Change Research Program (USGCRP). CCSM provides NSF and DOE, its primary sponsors and partners in the overall USGCRP, a core modeling system for multiple purposes, including studies of past and current climate, and projections of future climate change.

More recently, and through the extensive use of the previous CSL allocation, additional capabilities have been added to the CCSM in order to address a wider range of pressing scientific questions. These include, for instance, an interactive carbon cycle in the land component and an ecosystem-biogeochemical module in the ocean component. There is also an updated atmospheric chemistry component, a global dynamic vegetation component, and land use changes due to human activity in the land component. A new version of the atmospheric component model allows scientists to study both the direct and indirect effects of aerosols on climate. The model can be run using the Whole Atmosphere Community Climate Model (WACCM), in order to better understand the role of the upper atmosphere in climate variability and change. There is also an early version of a land-ice component that can be used to simulate changes to the Greenland ice sheet and its role in future climate change (although, to date, the development of the land ice model has leveraged DOE computing resources almost exclusively). Since the most widely used description of a model with these capabilities is an “Earth System Model”, the supported model is now called the “Community Earth System Model,” or CESM. The release of Version 1.0 of CESM occurred in June 2010, and a large number of simulations with it are being conducted, many of which will contribute to the next assessment of IPCC.

This proposal for CSL resources (over the period from April 2011 through June 2012) is thus directed toward the continued testing, development and application of CESM that is required in order to meet a wide variety of community needs and keep the project at the forefront of international Earth system modeling efforts. Importantly, the transition to CESM has expanded community involvement in its development and application, and there continues to be community governance of all its activities. Accordingly, the objectives and priorities outlined in this proposal emanate directly from the community of scientists who participate in the management of the CESM project – the 12 CESM working groups and the CESM Scientific Steering Committee (SSC).

In particular, to prepare this proposal, first each working group consulted with their constituents to discuss model development goals as well as the production simulations required to contribute to important international assessment activities and address high priority scientific questions, especially those that benefit from analysis and interpretation by the broader community. The draft working group plans were then distributed and reviewed, revised, refined and prioritized through a process of exchange across the different working groups, with the goal of producing a coherent and coordinated plan for the use of the CSL resource over the upcoming period of performance. The plans and resource requests of the individual working groups, which appear as appendices, then served as the source material for further deliberation by the CESM SSC, whose membership consists of not only NCAR scientists but also scientists from universities and other government laboratories. The goal of the SSC in this proposal was to articulate the overarching development and production simulation priorities for the entire CESM project, as well as a more detailed description of the main development and production activities, the required computing resources, an estimate of the amount of data to be generated, and a management plan to deal with the data volume.

This process and the objectives outlined above were motivated by the constructive comments and suggestions of the CSL review board to previous CCSM CSL proposals. It is our hope that the review board finds the current proposal addresses its previous concerns and presents a more coherent overview of the testing, development and application needs of the CESM project.

Major Deliverables from the Previous CSL Allocation

The development and application of the CESM and its predecessor (CCSM) involves not only the CSL computing resource, but also other computing resources such as the DOE INCITE (Innovative and Novel Computational Impact on Theory and Experiment) award, other national laboratory computing facilities, and work performed at university computing centers by individual members of CESM working groups. Nevertheless, CSL computer resources remain the lifeblood of the CESM project, and without them the many notable achievements since the last CSL award would not have been possible, including the community release of CCSM4.0 (in April 2010) and CESM1.0[1], and the completion of many simulations being made available for broad community analysis in support of the Fifth Assessment Report (AR5) of IPCC.

The following is only a brief overview of some of the major model developments and achievements under the previous CCSM CSL allocations (CCSM "Science" and CCSM "IPCC"). More detailed summaries (by working group) can be found in the CSL Accomplishments Report.

a. Model Development

CAM: The Community Atmosphere Model (CAM) version 5.0 (CAM5.0) has been modified substantially with a range of improvements in the representation of physical processes. New

[1] Although CESM1.0 supersedes CCSM4.0, users can run equivalent CCSM4.0 experiments from the CESM1.0 code base.

moist turbulence and shallow convection schemes more seamlessly simulate dry and moist boundary layer physical processes. Stratiform microphysical processes are represented by a two-moment (mass and number) formulation for cloud liquid and cloud ice that allows for ice supersaturation and predictive activation of aerosols to form cloud drops and ice crystals. The radiation scheme has been updated to the Rapid Radiative Transfer Method for GCMs (RRTMG) and employs a more efficient and accurate method for calculating radiative fluxes and heating rates. The 3-mode modal aerosol scheme (MAM3) has been implemented and provides internally mixed representations of number concentrations and mass for an expanded range of aerosol species. These major physics enhancements permit new research capability for assessing the impact of aerosols on cloud properties. In particular, they provide a physically based estimate of the impact of anthropogenic aerosol emissions on the radiative forcing of climate by clouds.

CAM-CHEM: The CAM Chemistry Model (CAM-CHEM) is now fully interactive and implemented in CESM; in particular, emissions of biogenic compounds and deposition of aerosols to snow, ice, ocean and vegetation are handled through the coupler. The released version of CAM-CHEM in CESM1.0 uses the recently-developed superfast chemistry, in which the number of chemical species and chemical reactions has been considerably reduced from the standard set (trop_mozart) without significantly affecting the representation of tropospheric ozone and its response to perturbations. The implementation of superfast chemistry allows centennial-scale simulations at a minor cost increase over the base CAM4.0. Historical simulations use the recently developed 1850-2005 emissions created in support of CMIP5.

CAM-WACCM: WACCM4.0 incorporates several improvements and enhancements over the previous version (3.1.9). It can be run coupled to the CESM ocean and sea ice model components. The chemistry module has been updated according to the latest JPL-2006 recommendations; a quasi-biennial oscillation may be imposed (as an option) by relaxing the winds to observations in the Tropics; heating from stratospheric volcanic aerosols is computed explicitly; the effects of solar proton events are included; the effect of unresolved orography is parameterized as a surface stress (turbulent mountain stress), which leads to an improvement in the frequency of sudden stratospheric warming; and gravity waves due to convective and frontal sources are parameterized based upon the occurrence of convection and the diagnosis of regions of frontogenesis.

CLM: The Community Land Model (CLM) was modified substantially and includes several new capabilities, input datasets, and parameterization updates. The model has been extended with a carbon-nitrogen (CN) cycle model that is prognostic in carbon and nitrogen as well as vegetation phenology. A transient land cover change capability, including wood harvest, has been introduced and the dynamic vegetation model was merged with CN (CNDV). An urban model has been added. The hydrology scheme was updated with a TOPMODEL-based runoff model, a simple groundwater model, a new frozen soil scheme, a new soil evaporation parameterization, and a corrected numerical solution of the Richards equation. The snow model was improved through the inclusion of aerosol deposition, grain-size dependent snow ageing, and vertically resolved snowpack heating as well as new snow cover fraction and snow burial fraction parameterizations. CLM4.0 also includes a new canopy integration scheme, revised canopy interception scaling, and a representation of organic soil thermal and hydraulic properties. The ground column is extended to ~50-m depth by adding 5 bedrock layers (15 total layers). New surface datasets based on MODIS products have been derived, providing a basis for the transient land cover datasets. To improve global energy conservation, runoff is split into separate liquid and ice water streams that are passed separately to the ocean model. Glacier land units can be partitioned into multiple elevation classes, with a distinct surface mass balance computed for each class. The surface mass balance is passed to the dynamic ice sheet model via the coupler and downscaled to the ice sheet grid.

CICE: The sea ice component is now CICE, the Los Alamos Sea Ice Model, sometimes referred to as the Community Ice CodE. The main areas of enhancement supported by CSL resources fall into two categories: physics and computation. The scientific enhancements include new tracers, a new shortwave radiative transfer scheme, improvements to the mechanical redistribution scheme, a melt pond scheme, and aerosol deposition, all applied to the snow and sea ice. The new computational enhancements include more flexible computational decomposition strategies, high resolution support, parallel input/output, and OpenMP threading capability.

POP: The ocean model has been updated to the Parallel Ocean Program version 2 (POP2) of the Los Alamos National Laboratory. Many physical and software developments have been incorporated using CSL resources. The physical improvements include a near-surface eddy flux parameterization; an abyssal tidally driven mixing parameterization; an overflow parameterization to represent the Denmark Strait, Faroe Bank Channel, Weddell Sea, and Ross Sea overflows; a sub-mesoscale mixing scheme; vertically-varying thickness and isopycnal diffusivity coefficients; modified anisotropic horizontal viscosity coefficients with much lower magnitudes than in CCSM3.0; and modified K-Profile Parameterization that uses horizontally-varying background vertical diffusivity and viscosity coefficients. The software developments include capability for multiple time-averaged history files and space-filling curves. The number of vertical levels has been increased from 40 levels (in CCSM3.0) to 60 levels (in CESM1.0). POP2 also includes passive tracer infrastructures. A marine ecosystem-biogeochemistry module has been incorporated that simulates the evolution of multiple plankton species, primary productivity, nutrients, iron, oxygen and inorganic and organic carbon. The module is also the basis for the oceanic component of the CESM coupled carbon cycle experiments.

Infrastructure: Novel infrastructure capabilities in CESM1.0 permit new flexibility and extensibility to address the challenges involved in Earth system modeling. An integral part of CESM1.0, developed with CSL resources, is the implementation of a coupling architecture that provides the ability to use a single code base in a start-to-end development cycle – from model parameterization development (that might only require a single processor) to ultra-high resolution simulations on High Performance Computing (HPC) platforms using tens-of-thousands of cores. The CESM1.0 coupling architecture also provides “plug and play” capability of data and active components and includes a user-friendly scripting system and informative timing utilities. Together, these tools enable a user to create a wide variety of “out-of-the-box” experiments for different model configurations and resolutions and also to determine the optimal load balance for those experiments to ensure maximal throughput and efficiency. CESM1.0 is also targeting much higher resolutions than any previous CCSM coupled model and efforts have been made to reduce the memory footprint and to improve scaling in all components (see section on model performance below).

Data Models: The CESM1.0 data models have been completely rewritten. They are now parallelized and share significant amounts of source code. In particular, methods for reading and interpolating data have been established that can easily be reused.

b. Scientific Simulations

There have been a large number of scientific simulations performed under the previous CSL allocation, and many have been widely accessed and utilized by working group participants or even broader communities. These include, for instance, simulations that have contributed to the model development activities under CLIVAR Climate Process Teams (CPTs) and contributions to coordinated modeling studies performed under the auspices of both international and national research programs and modeling activities. One example of scientific experiments performed under the past CSL allocation were those designed to test the climate impacts of the North Atlantic and Antarctic overflows, as well as simulations to study the processes associated with variations in the Atlantic Meridional Overturning Circulation (AMOC) and their impact on climate. Others include simulations to examine the climate impact of urban landscapes, the impact of seasonal sea ice losses on heat and freshwater fluxes, evaluations of the present-day carbon cycle and its interactions with nitrogen and phosphorus biogeochemical cycles, studies of the mechanisms responsible for sudden stratospheric warming events, simulations of the Pliocene and several other past periods of Earth history, studies assessing uncertainties in simulations of future climate, and studies assessing drought genesis and maintenance over North America.

CMIP5: The major use of CSL resources, however, has been toward completing a core set of long-term climate change simulations in support of AR5. Moreover, since writing the 2009 CSL IPCC proposal, several notable developments and improvements have allowed CESM to pursue a more ambitious set of simulations than were originally proposed. Like other major international modeling centers, CESM is following the CMIP5 Experimental Design, which means there are two distinct foci for current model experiments: (1) near-term, initialized decadal prediction simulations (10-30 years); and (2) long-term simulations from about 1850 through the end of the current century and beyond, using both CCSM4.0 and CESM1.0. The former required developing the capability to initialize CCSM4.0 with the observed state of the ocean by assimilating global temperature and salinity observations. Developing this capability with the CISL Data Assimilation Research Testbed (DART) required the use of CSL resources, although all of the near-term initialized experiments are being run on DOE computers. In contrast, the "core," as well as many of the lower priority "tier-1" and "tier-2", long-term simulations are being performed at NCAR.

The long-term simulations include coupled carbon cycle experiments, and the CSL allocation has been crucial to developing this capability. Also, as mentioned earlier, CESM1.0 employs several new configurations of the atmosphere, including CAM5.0, WACCM4.0 and CAM-CHEM. Thus, largely through CMIP5 simulations employing various configurations of the model, the CESM research community has the opportunity to pursue many key scientific questions that could not be pursued with previous versions of the model (e.g., estimating the indirect aerosol effect in 20^{th} century and future climate simulations, examining the role of the upper atmosphere processes in climate variability and change, and examining how carbon sources and sinks are likely to change in the future). When the CCSM/CESM IPCC AR5 simulations are completed, the community will therefore benefit from an extremely ambitious suite of experiments with a hierarchy of state-of-the-science models.

Under the previous CSL proposal, the CESM project has completed (on-schedule) a significant fraction of the CMIP5 long-term simulations. Most have employed a spatial resolution of 1 degree in both the atmosphere and ocean, which is higher than the 2 degree atmospheric resolution discussed in the previous CSL proposal. There are many improvements in the simulated climate at the higher atmospheric resolution, and these were judged to be of enough significance to make the 1 degree version of CCSM4.0 the "workhorse" model for CMIP5. Simulations performed with CSL resources include long (>1,000 year) pre-industrial control integrations of CCSM4.0 and CESM1.0 with and without interactive carbon and ensembles of 20th and 21st century simulations (for RCP 2.6, 4.5 and 8.5, with RCP 6.0 simulations completed before April 2011). In addition, pre-industrial controls, 20th century and some 21st century simulations with WACCM and CAM-CHEM as the atmospheric components of CESM1.0 have also been completed.

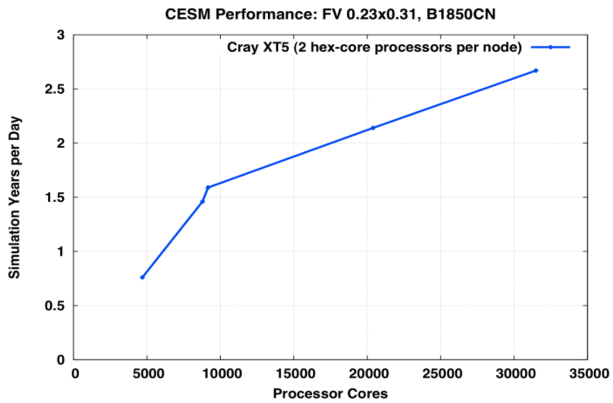
c. Model Performance

With the development of CESM1.0, great strides have been made using the CSL resource in optimizing both the performance scalability and efficiency for a variety of model resolutions, physics, and computational platforms. In particular, since the release of CCSM3.0, the model code base has migrated from the O(100) processor, O(100-km) model operating space to an O(10 km) version of the system capable of running on many thousands of processors. Key components of this new capability have been the introduction of new coupling architecture, CPL7, parallel I/O throughout the model system, and enabling hybrid MPI/OpenMP functionality in every CESM component. CPL7 has introduced a completely new approach to the high-level architecture and design of the system. CESM1.0 is now a single executable system that has the flexibility of running model components sequentially, concurrently, or in a mixed sequential/concurrent mode. Furthermore, the new design guarantees that the results of a given simulation are independent of the component processor layouts chosen. Additional timing diagnostics now accompany every job submission, thereby permitting users to easily determine an optimal load balance for the given experiment.

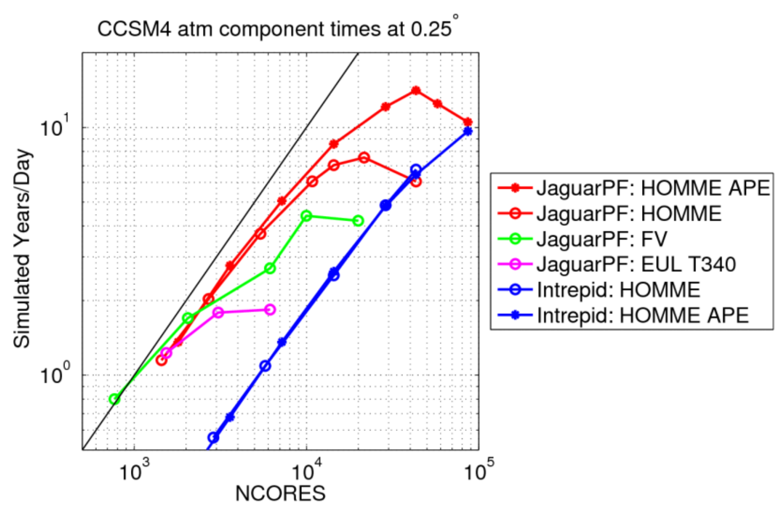
CESM1.0 has also been accompanied by the introduction of a new parallel I/O library, PIO, into every model component. Previously, the CCSM model system limited external storage accesses to a single master process, thereby creating a serial bottleneck, degrading parallel performance scalability of the application as a whole, and/or exhausting local memory. On the other hand, allowing all processes to access the external storage, especially access to the same file, can lead to very poor performance when thousands of processes are involved. One of the key features of PIO is that it takes the model's decomposition and redistributes it to an I/O "friendly" decomposition on the requested number of I/O tasks that can be different from the number of model MPI tasks. PIO also currently supports serial NetCDF, parallel pnetCDF and MPI IO, and NetCDF4.

The above improvements to the CESM have been leveraged to optimize both the throughput and efficiency of experiments, as shown in the working group GAU requests (see the appendices). However, it is important to also point out that these improvements have enabled petascale readiness across the CESM model system, an issue of concern raised in previous CCSM CSL proposal reviews. In what follows, we therefore briefly summarize this critical new capability, especially with the advent of the NCAR-Wyoming Supercomputing Center (NWSC) in 2012.

The most computationally expensive CESM configurations have a 0.1° resolution ocean (POP) and sea ice (CICE) resolution. The following plot (courtesy of Pat Worley) shows performance in simulated years per day of CESM with 0.1° POP and CICE with 1/4° CLM and CAM4 with the finite-volume dynamical core.



The release of CESM1.0 has also been accompanied by the introduction of the HOMME spectral element dynamical core in CAM, which should permit the model to scale out to much higher processor counts than the current FV dynamical core. In the coming year, it is expected that high-resolution CESM configurations will see increasing use of this spectral-element dynamical core. The following plot (courtesy of Mark Taylor) shows the relative performance of CAM4 with these various cores at 1/4° resolution (CCSM4.0 is equivalent to CESM1.0 configured for high resolution). FV is the finite-volume dynamical core, EUL T341 is the spectral dynamical core, HOMME is the spectral-element dynamical core, and HOMME APE is the spectral-element dynamical core run without land ("aquaplanet").



When coupled with 0.1° POP and CICE, which scale up to about 50k cores of Jaguar, the spectral dynamical core will allow effective use of about 55,000 cores, the finite-volume dynamical core will allow about 60,000 cores, consistent with the previous plot, and the spectral-element dynamical core will allow almost 100,000 cores at 1/4° resolution. It is important to note that the CPL7 architecture is utilized in all non-aquaplanet simulations, thereby demonstrating that the scalability of the dynamical core is preserved by CAM *and* the scalability of CAM is preserved by CESM, even when CAM is coupled to realistic land, ocean and sea-ice components at different resolutions.

Overarching Priorities

The full suite of CESM development and production plans extend beyond those described in this CSL proposal. They involve, for instance, the activities of many working group scientists, and perhaps especially those of CESM collaborators and working group co-chairs at the DOE National Laboratories. CESM development activities also result from CESM working group participation in activities such as the CLIVAR CPTs, as well as from the involvement of CESM scientists with university collaborators in agency proposals, including the recent NSF/DOE/USDA call for decadal Earth system prediction capabilities. Longer-term CESM development activities are also facilitated by the recent DOE proposal “Climate Science for a Sustainable Energy Future”, which involves the direct participation of several CESM working group co-chairs and focuses on reducing uncertainty and confronting models with observations with the aim of developing the “next generation plus one” version of CESM (i.e., CESM3.0). Yet, it is the CSL resource that remains essential for CESM development, and without it the modeling system could not survive as one of international repute. In particular, it is noteworthy that the CSL computational facility is not only familiar to CESM scientists and software engineers, but is also robust and reliable and is optimized for CESM production runs. CSL also provides fast network connections for output transfer and analysis and the means to easily share data with the broader community. No other computational facility currently offers this combination of advantages for CESM development and production activities.

In what follows, we summarize the overarching development and production priorities across the working group requests[2]. Previous CCSM CSL reviews have requested the project attempt to better delineate between development and production activities. The defining characteristic of production simulations is that they have broad appeal across the climate science community and are thus made available for community access and analysis, following the procedures outlined in the CESM data policy. Examples include simulations that contribute directly to coordinated national or international modeling activities and “benchmark” simulations that document CESM components and new coupled configurations of the model (e.g., control and transient simulations). Both are examples of simulations where the project benefits directly from analysis and interpretation by the broader research community.

The outcome of community analysis often leads to new insights into model behavior and new development efforts, so that development and production activities are synergistic and sometimes

[2] The overarching priorities for each individual working group are also described in the appendices. Throughout, the main body of this proposal and the more detailed appendices follow the same format.

become blurred. In contrast to production simulations, however, development simulations may, or may not, be made available for analysis beyond the working group members who produce the runs. They include, for instance: simulations to understand CESM (or component) behavior, document biases, and determine the responsible processes; efforts to improve the representation of processes; and activities to add new capabilities to CESM important for improving simulation fidelity, for new community-based science, and for future releases.

a. Overarching Development Priorities

The development simulations in the more detailed working group requests (see the appendices) are broadly summarized below in terms of five overarching themes: (1) coupling across components and understanding interactions; (2) new parameterizations and processes; (3) high resolution and new dynamical cores; (4) addressing biases and other known shortcomings; and (5) software development.

Coupling across components and understanding interactions. A key attribute of CCSM4.0 and CESM1.0 is the ability to simulate coupled interactions across different components of the climate system, including physical, chemical and biological elements. Proposed development work in this regard focuses on three main aspects: evaluating model performance against observations; understanding the behavior of and refining the representation of physical processes; and expanding capabilities for coupling across components.

Model-data evaluation will be conducted by incorporating new diagnostics (e.g., Arctic Ocean freshwater tracers; isotopes for paleoclimate studies) and creating better tools for systematic assessments (e.g., a land-model test-bed; ocean data assimilation techniques). Assessment efforts will facilitate further analysis of model biases (both known and as yet unidentified, see below) and feed into parameter sensitivity studies for component models and fully coupled simulations (e.g., prescribed aerosol version of CAM5; atmospheric convection schemes; ocean anisotropic viscosity). New coupling capabilities are required for ocean freshwater exchange as a result of the incorporation of a dynamic land-ice model. For several of the working groups, model assessment and parameterization efforts will leverage collaborative activities by groups at the DOE national laboratories and with CPTs.

New parameterizations and processes. To address the evolving scientific needs of the CESM community, progress demands that new processes be introduced and new parameterizations of existing processes be developed and tested. Certainly, all of the working groups have specific plans for development and testing of new process models for each of the CESM components. Overarching priorities are to improve the simulation of the radiative forcing of climate change by greenhouse gases (CO_2, ozone, and methane) and aerosol (secondary organic aerosol), as well as improve the treatment of the feedback of climate change involving the greenhouse gases, the aerosol, clouds, and the cryosphere.

These goals will be principally achieved by: improving gas chemistry to better simulate ozone, methane, and secondary organic aerosol; introducing double moment microphysics into cumulus cloud parameterizations so that aerosol effects on cumulus clouds can be represented; introducing dynamic land units, methane emissions and prognostic wetland distribution to the land model; improving the representation of bottom topography in the ocean model to better simulate ventilation; improving the simulation of the ocean alkalinity cycle by introducing another calcifying functional group to the ocean model and including feedbacks between simulated carbonate chemistry and biological activity; and improving the treatment of snow aging, melt ponds, and Arctic biogeochemistry.

High-resolution and new dynamical cores. The major directions for the development of high-resolution and new dynamical cores for CESM are: testing and evaluating CAM and coupled CESM performance (with and without chemistry) at resolutions up to 0.25° using the Finite-Volume dynamical core; testing and evaluating CAM performance (with and without chemistry) at resolutions up to 0.25° using the Higher-Order Method Modeling Environment **(**HOMME) dynamical core; and carbon cycle simulations at 0.5° resolution. These priorities are in close alignment to the requirement of developing the next generation of models that can run efficiently on large processor counts on petascale and beyond computers such as the NWSC or many of the DOE supercomputers.

In particular, the simulations proposed by working groups under the first two goals aim at evaluating (comparison against observations) and understanding the behavior of the atmospheric model (under present-day and past climate conditions) and of atmospheric chemistry when resolution is incrementally increased from, currently, the nominal 1.9° x 2.5°. Particular attention will be given to the change (either improvement or deterioration) in model biases and analysis of convergence. Similar analysis will be performed when the recently developed dynamical core HOMME is used instead of the Finite Volume dynamical core that has been used in CCSM4.0 and CESM1.0 CMIP5 simulations. In addition, high-resolution land modeling will enable the participation of CESM in the Global Carbon Project (of the International Geosphere-Biosphere Project, IGBP) for terrestrial carbon model evaluation.

Addressing biases and other known shortcomings. While there is early indication that CMIP5 simulations (using CCSM4.0 and CESM1.0) exhibit reduced biases in several important variables relative to earlier model versions, significant shortcomings remain to be addressed. For example, in the simulated atmosphere, issues such as the double inter-tropical convergence zone (ITCZ) and an excessive tropical water cycle remain. More generally, biases are present in all aspects of CESM1.0 and their influence propagates throughout the fully coupled system. Such is the case for areas with too low ocean ventilation, creating hypoxic zones affecting the oceanic biogeochemical cycles and ultimately the carbon cycle.

The main working group requests for addressing biases and known issues are focused on the following aspects: CAM5 physics, and in particular the too-strong indirect effect; the representation of stratospheric dynamics and chemistry, stemming in part from the participation of CESM in a recent model inter-comparison exercise under the auspices of the World Meteorological Organization (WMO); and land and ocean biogeochemistry, with a particular focus on the Polar regions. All requested simulations span multiple working groups and, as such, positive outcomes will have significant implications to the representation of the coupled system and benefit the overall CESM community.

Software development. The request for software development under testing covers three traditional and well-defined tasks: model testing; performance tuning; and debugging. These service activities have proven their worth. They are essential for efficient and broad community use of CESM. Every combination of model configuration and production machine undergoes 115 short tests to ensure reliability before being made available for community use. Allocations are also requested for debugging problems as they arise inevitably from systems issues, or from new dynamic capabilities and parameterizations, processor layouts and resolutions. Performance tuning optimizes the number of MPI tasks and OpenMP threads for each CESM component, resolution and targeted processor count. Therefore, the requested computing resources can be regarded as a wise investment with a high return in the forms of reducing computing with problematic code, centralized debugging by experts, and efficient use of allocated processors.

Performance tuning is taking on added significance with the prospect of the NWSC and the trend to higher resolution simulations requiring very high processor counts. These efforts were described previously under “Model Performance”.

b. Overarching Production Priorities

The production simulations in the more detailed working group requests (see the appendices) are broadly summarized below in terms of three overarching goals: (1) contributions to nationally or internationally coordinated modeling and assessment activities; (2) benchmark simulations that document components and new capabilities of CESM; and (3) climate variability and predictability experiments of value to the broader community. Cross-cutting activities between different CESM working groups are highlighted, although it is noteworthy that many other production requests in the appendices are appropriate for individual working groups without the need for explicit coordination and resource sharing.

Coordinated modeling and assessment activities. The CESM project contributes extensively to climate assessments and Earth System process evaluation projects coordinated at national and international levels. Such contributions are a central part of the CESM mission, and the CSL resource is critical in order to maintain this commitment. Activities include:

CMIP: Simulations in support of IPCC AR5, following the CMIP5 experimental protocol, were the central component of the previous CSL production request. Tremendous progress was made, and much of this ambitious set of simulations will have been completed by April 2011. However, several important (but less time critical) CMIP5 simulations remain. They include, for instance, simulations designed to: separate the effect of radiative forcing from ocean coupling in projected climate change; support comparisons to satellite data; investigate the biogeochemical effects of land cover change; diagnose equilibrium climate sensitivity; and further investigate atmospheric chemistry and composition. The latter will also contribute to the Atmospheric Chemistry and Climate Initiative (AC&C) – a joint effort of WCRP and IGBP, with leadership provided by the IGAC (International Global Atmospheric Chemistry) and SPARC (Stratospheric Processes and their Relation to Climate) projects of those international research programmes.

GeoMIP: The CESM project will contribute to international efforts to assess the science and consequences of different approaches to “Geo-engineering”, which is the study and implementation of technical ways to counter some of the likely consequences of global warming. Chief among these is the Geo-engineering Model Intercomparison Project (GeoMIP), which explores the response of coupled climate system models to a reduction of solar radiation reaching Earth's surface (e.g., from the introduction of stratospheric aerosols into the atmosphere).

PCMIP and C^{4}MIP: The CESM project will contribute to the Paleoclimate Model Intercomparison Project (PCMIP) and the Coupled Carbon Cycle Model Intercomparison Project (C^{4}MIP). The PCMIP is an international activity that will combine carbon cycle and paleoclimate modeling with ice-core and other paleoclimate records to quantify carbon-cycle climate feedbacks. Its goal, in coordination with C^{4}MIP, is to use knowledge about past variations in climate and CO_2 to provide additional constraints for understanding the magnitude of the carbon-climate feedbacks.

WGNE/WGCM Weather/Climate Activities: The CESM project will participate in international projects designed to assess the short-term behavior of climate models when they are run in weather forecast mode. These simulations, designed by the WMO Working Group on Numerical Experiments (WGNE) and the WCRP/CLIVAR Working Group on Coupled Models (WGCM), expose the source of climate biases and systematic error by testing fast process errors that lead to forecast error and climate drift.

Community Ocean Process Studies: The CESM project will participate in both CPT activities and the international CLIVAR Coordinated Ocean-Ice Reference Experiments (CORE). The CLIVAR CORE experiments represent an international effort to compare the behavior of ocean-only and coupled ocean/sea-ice simulations under consistent atmospheric forcing datasets, using either normal year or interannually varying forcing. The concept behind CPTs funded by U.S. agencies is to coordinate observational and process modeling activities in order to rapidly improve climate models. CPT-related production requests will primarily test ocean processes, with an emphasis on high latitudes, with the results made available for analysis by the ocean and polar process communities.

SIMMER: The CESM project will contribute to the SIMMER (System for Integrated Modeling of Metropolitan Extreme Heat Risk) project, which assesses current and future urban vulnerability from heat waves through integration of physical and social science models, research results, and satellite data.

Benchmark simulations. A major objective for the CESM community is to explore and document new capabilities of the model, including novel representations of Earth system processes and their interconnections, and new developments in component models including how they impact the coupled climate and climate sensitivity. Benchmark simulations involve both control (e.g., pre-industrial and present day) and transient climate change experiments, and it is essential that they are made available for analysis and assessment by the broad research community.

The CESM1.0 includes many new processes and capabilities, and even since the release of the model in June 2010, still newer parameterizations and numerics need to be assessed. These fall into several broad categories: a new land ice component; new carbon cycle components; improvements in the biophysical simulation of different land covers; improvements in the atmospheric model; evaluation of low resolution and/or simplified versions of the model;

evaluation of higher resolution versions of the model; and evaluation of water isotopes in the model.

Climate variability and predictability experiments. Earth Systems Models represent a central tool to quantify uncertainty and enhance understanding of climate variability on time scales from the sub-seasonal to the multi-decadal. The first version of CESM has not been fully characterized in the context of its representation of the past climate and its projections of future climate. Such characterization requires, for instance, large ensembles of simulations designed to characterize the spread of climate predictions generated by internal variability, the role of polar processes in determining climate sensitivity, and the role of patterns of oceanic surface temperature in generating atmospheric variability.

Specific Experiments and Resource Request

The overarching development and production simulation priorities for the entire CESM project, described above, are now discussed in terms of more specific activities and experiments, as well as the required computing resources. Even more precise descriptions, and a more comprehensive list of experiments, can be found in the individual working group requests (see the appendices), which also describe model configurations and costs associated with each experiment. An estimate of the amount of data to be generated, and a management plan to deal with the data volume, is provided in Section 5.

a. Development Activities and GAU Request

Coupling across components and understanding interactions

Aerosol. CAM5 was developed using a prognostic version of the Modal Aerosol Model (MAM), requiring an additional 20 species to be transported by the finite volume tracer advection scheme. This results in a significant computational overhead that approximately doubles the overall cost of running CAM. Furthermore, the inclusion of interactive aerosol in CAM5 and its new capability to directly influence size and number of in-cloud ice and liquid cloud particles introduces an extra degree of freedom. This makes it difficult to disentangle the cause-and-effect relationships of cloud-aerosol interactions, particularly in future climate scenarios. The CESM project intends to develop a prescribed-aerosol version of CAM5 (CAM5-PA) that will provide a more comparable version to CAM4 both in terms of functionality and cost. Equally important, this new configuration will allow for faster and cheaper testing and evaluation of the representation of cloud-aerosol interactions.

Data assimilation. An important requirement of decadal prediction simulations is the specification of ocean initial conditions. As an alternative to initial conditions extracted from ocean sea-ice coupled hindcast simulations, CESM has been exploring the use of a data assimilation system, in collaboration with the Data Assimilation Research Testbed (DART) effort at NCAR, to obtain ocean initial states constrained by historical observations. This process, however, remains computationally inefficient. Therefore a request for resources is made to explore approaches leading to improved efficiency. Among other applications, data assimilation, and its systematic comparison with observations, is an ideal tool for the identification of systematic errors in the coupled model.

Arctic Ocean biogeochemistry. Initial analysis suggests that there are substantial biases in Arctic Ocean biogeochemical fields within CESM. At present, it is not clear whether these result from poor parameterizations of local processes or if the biogeochemical effects of Pacific and Atlantic inflows are poorly represented. A series of experiments are proposed to determine controls on the Arctic Ocean N, P, C, and oxygen budgets. A series of experiments will be performed to determine the sensitivity of budgets to physical and ecological variables. Of particular interest is the effect of terrigenous material on nutrient budgets. These fluxes are not represented in the current release of the model.

New parameterizations and processes

Improved physics. Several improvements to CAM5 and WACCM, which will be updated to CAM5 physics, are planned. These include combining the shallow and deep convection schemes to provide a unified convection capability, the extension of the existing shallow convection parameterization to perform deep convection, the extension of the existing Morrison-Gettelman microphysics scheme to more realistically represent microphysical processes in deep convection, and implementing the turbulent mountain stress scheme in a more robust and resolution invariant manner. An improved function for gravity wave (GW) generation from frontal and baroclinic sources will be developed. The ‘frontogenesis’ function currently used neglects GW generation from upper level jets as well as strong wind shear regions in the lower stratosphere.

The land model will also be subject to significant improvements including a revised lake model that: fixes problems with the surface energy budget and mixing; reduces errors in partitioning fluxes; and incorporates better phase change physics. The canopy absorption of solar radiation will be extended to consider spherical elements which provide several advantages including more accurate representation of ground shading at high zenith angles. A revised fire algorithm that accounts for deforestation fires and explicitly considers human caused ignition and fire suppression as a function of population density will be incorporated.

Algorithmic and numerical issues associated with freshwater fluxes to the ocean will be corrected through the elimination of a linear assumption in the barotropic solver as well as implementation of the so-called z* vertical coordinate to address the possibility of thin uppermost layers.

Methane emissions. A methane emissions model that includes process-based representations of CH_4 production, oxidation, transport through plant roots and shoots (via aerenchyma channels), ebullition, aqueous and gaseous diffusion, and fractional inundation has been developed at LBNL and needs to be incorporated into CLM. The CESM project plans to test the methane emissions model coupled to the atmosphere and verify that the model can reproduce observed fluctuations in atmospheric methane, using best available information about other sources of methane. This effort will bridge several CESM working groups (Land Model, Biogeochemistry and Chemistry-Climate).

Land ice. The surface mass balance of glaciers and ice sheets is sensitive to the albedo, which can vary significantly as a function of local conditions. In CLM the snow albedo is computed using the sophisticated SNICAR scheme, but the bare ice albedo is parameterized simply as a pair of numbers (broadband albedo in the visible and near IR bands, respectively). The treatment of bare-ice albedo will be improved by implementing a physically-based broadband albedo parameterization. The resulting changes in the surface mass balance of the Greenland ice sheet will then be analyzed. Much of the validation and analysis can be done in the inexpensive configuration of active land ice plus active CLM with prescribed atmospheric forcing.

High-resolution and new dynamical cores

The inclusion of the spectral-element based HOMME dynamical core on a cubed sphere grid is not only science driven, but it is a promising approach for improved computational scalability. This is a high priority since the next-generation NCAR computing facility is expected to have processor numbers of the order of 100,000 and the finite volume dynamical core is ill-suited to efficiently exploit large numbers of processors. The CESM project intends to investigate and document the climate characteristics of CAM-HOMME across a range of resolutions in order to complement other DOE computational scaling activities. Shorter-term experiments will be performed at much higher resolutions to investigate and document the interaction of dynamics and parameterized physics at high resolution (nominally 0.25º). The Atmosphere Model Working Group will work closely with the Chemistry-Climate Working Group and the Whole Atmosphere Working Group to investigate chemistry implementation in these high-resolution simulations.

The sensitivity to vertical resolution in CAM remains poorly understood. Two lines of research will be pursued: elevating the upper boundary (model top) in CAM to fully encompass the stratosphere, and increasing the number of vertical levels up to a doubling of the current CAM5 resolution (60 levels).

Addressing biases and other known shortcomings

Biases are present in all aspects of CESM1.0 and their influence propagates throughout the fully coupled system. Thus, while we categorize biases by model component in the following description, proposed development simulations span multiple working groups (and several examples are highlighted). Thus, these development simulations will have significant implications to the representation of the fully coupled system.

Atmosphere. Significant mean biases to be investigated and addressed include: weak clear-sky long-wave radiative forcing, low in-cloud water concentrations, strong cloud-aerosol interactions and radiative effects. In addition, long outstanding coupled biases such as the double ITCZ, an excessive tropical water cycle, and variable cloud-feedbacks during ENSO will be addressed. In the stratosphere, there is a clear bias in the strength and position of the Southern Hemisphere stratospheric jet. This could be responsible for some of the biases in the representation of the Antarctic ozone hole, along with possible deficiencies in the chlorine chemistry. The representation of isoprene chemistry is unrealistic and the impact of isoprene on OH may even be of the wrong sign. This impacts longer-lived species such as methane and carbon monoxide, both ozone precursors. A systematic analysis of emerging isoprene chemistry mechanisms will be conducted.

Land. Several biases related to both model biogeochemistry and biogeophysics in CLM will be addressed with CSL resources. Biogeochemical biases including a high gross primary productivity (GPP) in the tropics, generally excessive maximum leaf area indices, and errors in the timing and phase of vegetation phenology. Vegetation carbon content is too high in the tropics and too low over much of the mid- and high-latitudes. Soil carbon stocks appear to be somewhat low everywhere and are very low across the northern high-latitudes. Biogeophysical biases include unrealistically dry Arctic soils which leads to excessively cold soil temperatures and to poorly growing vegetation, especially in permafrost zones and low snow-season surface albedos over the boreal forests. Soil moisture variability remains low near the surface and lake temperature profiles and surface energy budgets are unrealistic. Several of the biases that have been identified are related to interactions between model biogeophysical and biogeochemical processes. One of the aims of the Land and Biogeochemistry working groups is to better integrate the biogeophysical and the biogeochemical model development through the development of a land model testbed in which the biogeophysical and biogeochemical performance of the model can be evaluated in a systematic and coordinated fashion.

Ocean. The abyssal Pacific Ocean in CESM is poorly ventilated relative to observations; therefore, the water is too old and void of oxygen. This poses numerous problems for the ocean ecosystem model as well as the interpretation of ocean sediment cores. The CESM project will explore the hypothesis that poorly represented bottom topography leads to this ventilation problem, primarily by blocking of important deep-water passageways. Because the problem is already evident in the forced ocean-only configuration, this hypothesis can be initially tested without a fully coupled model: the sensitivity of the deep ocean properties to differently smoothed and/or modified bottom topography will be explored through ocean-only simulations.

Software development. Resources are requested to run the CESM test suite, the amount of which would permit the capability of having two-to-three new development versions and a release update to be created each month.

The following Table summarizes the Working Group Development Requests.

Working Group	**Development Request (kGAU)**
Atmosphere Model Working Group	894.8
Biogeochemistry Working Group	471.4
Chemistry Climate Working Group	549.5
Land Ice Working Group	410.0
Land Model Working Group	750.0
Ocean Model Working Group	771.5
Paleoclimate Working Group	436.4
Polar Climate Working Group	244.7
Software Engineering Working Group	600.0
Whole Atmosphere Working Group	913.0
TOTAL	**6041.3**

b. Production Activities and GAU Request

Simulations under the following three overarching production themes each account for roughly one-third of the total production resource request.

Coordinated modeling and assessment activities

CMIP: The Biogeochemistry, Climate Change, Chemistry Climate and Whole Atmosphere working groups will all contribute to several important (remaining) CMIP5 simulations. Experiments include new configurations of CESM for future scenarios of climate change, elucidating biogeochemical impacts of land cover change, running decadal prediction experiments of air quality accounting for tropospheric chemistry, and contributions to the CFMIP subproject for assessment of cloud radiative forcing. As mentioned earlier, some of these experiments will also represent the CESM contribution to AC&C.

GeoMIP: The Whole Atmosphere, Chemistry Climate and Climate Change working groups are contributing to GeoMIP via CESM configurations with the atmospheric component CAM4.0. Analogous experiments with CAM5.0 as the atmospheric component are relatively expensive; nevertheless, resources for such a companion set are being requested from DOE through a recently submitted proposal to NERSC. Comparison of the results will help in understanding the differences between these two climate models with very different behavior (climate sensitivity and cloud feedbacks), allow for more thorough comparisons to other models, and will provide a first look at some of the potential consequences of geo-engineering.

PCMIP and C^4MIP: The Paleoclimate working group will carry out a 500 year time slice simulation of the last glacial maximum using CESM with interactive carbon/nitrogen cycling at 1º resolution, in order to establish long-term atmospheric carbon dioxide concentrations and the effects of dust and sedimentary iron sources from sea level decrease.

WGNE/WGCM Weather/Climate Activities: The Atmospheric Model working group will carry out Transpose-AMIP simulations, a protocol designed to run climate models in weather-forecast mode. A number of global hindcasts are to be produced with both CAM4.0 and CAM5-PA, comprising 5-day integrations over 4 periods, sampling throughout the annual and diurnal cycles.

Community Ocean Process Studies: In support of the CPT projects described earlier, the Ocean Model and Polar Climate working groups will carry out simulations of ocean mixing processes at high latitudes, focusing on mixing in the presence of sea ice accounting for brine exchange and biogeochemical processes, and on the role of mixing by inertial waves in controlling Arctic halocline structure. In support of CORE, the Ocean Model working group will carry out a number of ocean-only and ocean-sea ice hindcast experiments.

SIMMER: The Land Model working group will carry out a series of offline high resolution simulations over the U.S. in support of the SIMMER project. These simulations will also support research activities for community users of the urban model.

Benchmark simulations

New land ice component: The latest version of the CESM includes a new land ice component. Experiments are proposed to simulate the evolution of the Greenland ice sheet under a variety of climate scenarios, including: (1) preindustrial and present-day conditions; (2) 21st century; (3) future long-term (beyond 2100); (4) previous interglacial periods; and (5) the Eemian time period. These simulations will be conducted under the leadership of the Land Ice working group, in coordination with the Land Model working group.

New carbon cycle component: CESM1.0 includes an active carbon cycle. In order to separate the importance of biophysical impacts of land use from biogeochemical processes, simulations will be conducted to isolate the biophysical effects (e.g. changing forests to agricultural). In addition, there is ongoing development of new carbon cycle processes, and these will need to be evaluated against released CESM1.0 experiments in both control and transient simulations. These simulations are proposed by the Biogeochemistry working group, in coordination with the Land Model working group.

Improvements in simulations of land cover types: New capabilities in the biophysical simulation of land cover types are being developed within the Land Model working group, and these will be assessed by the broader community using production runs. The specific capabilities to be tested are: relative importance of nitrogen deposition versus land use disturbance; irrigation on crop lands; and integration of the carbon-nitrogen model with the dynamic vegetation model. These simulations will be conducted by the Land Model and Biogeochemistry working groups.

Improvements in the atmospheric model: The climate of the lower resolution (nominally 1º) version of CAM-HOMME requires significant documentation to identify similarities and differences with the standard production FV-core CAM simulations. The Atmospheric Model working group intends to perform fully coupled experiments, initially using CAM4.0 physics, including a pre-industrial control as well as 20th century historical experiments to achieve this goal. In addition, the Whole Atmosphere working group proposes to evaluate the importance for climate of changes, based on new observations, in the spectral irradiance measurements.

Low resolution atmospheric models: Because of the expense of the fully coupled model, it is important to have a less costly version of the model for development work, as well as for certain applications (e.g., paleoclimate and biogeochemistry). The Atmospheric Model working group is thus developing a robust, low-resolution version of CAM using the finite volume dynamical core. Production simulations to fully evaluate the lower resolution version include long control simulations. In addition, the Biogeochemistry working group proposes simulations using the coupled low resolution model in control and transient simulations to evaluate the coupled-carbon-climate model relative to that in the CESM1.0 release used for IPCC AR5. Also, experiments to validate CAM5-PA as the atmospheric component of CESM include a pre-industrial control and 20th transient simulations.

High resolution: The Chemistry Climate working group proposes to conduct dynamical downscaling simulations coupled to a regional model to understand how climate change interacts with air quality. The Ocean Model working group proposes to conduct regional ocean simulations of the western boundary current and the coral triangle region. These will assess how resolution changes the details of the simulation of the North Atlantic, and issues like coral bleaching.

*Water isotope modeling***:** The Paleoclimate working group proposes to evaluate a new capability to carry water isotopes in the model, and compare to available observations.

Climate Variability and Predictability Experiments

Role of Arctic processes: The Polar Climate working group will oversee a series of simulations to evaluate cryospheric and hydrological processes over the Arctic in CESM1.0, including experiments to elucidate: high latitude freshwater budgets; drivers of sea ice variability and change; marine ecosystem behavior in polar seas; the influence of regional Arctic sea ice loss on the atmosphere; and the seasonal-to-interannual predictability of sea ice cover. These studies will involve new CESM capabilities (e.g. changes to circulation pathways in the ocean model and biogeochemical processes) and will also update previous work done with CCSM3.0.

Enhancing understanding of climate variability in the historical period: In order to assess the relative roles of anthropogenic and natural variability in explaining the observed climate record, the Climate Variability working group will carry out simulations with CAM4.0 in which all or part of the ocean surface temperature variability of the historical period is prescribed (as described by the AMIP and Pacemaker protocols detailed in their working group request). Such simulations represent the standard for evaluating large-scale atmospheric variability and its coupling to the ocean, and continue to be widely used in the community. In order to assess the effects of deep ocean variability in the coupled model, these experiments will be complemented by a multi-century integration of CAM4.0 coupled to a global slab ocean mixed layer.

Improved understanding of decadal predictability: The Polar Climate and Climate Change working groups (with input and analysis by members of the Climate Variability working group) together are proposing a 30-member ensemble of climate projections for the period 2005-2034. Goals for this considerable resource request, which has attracted significant community interest, include assessments of decadal predictability, quantification of model uncertainty, and formulation of probabilistic approaches to climate prediction. The previous large ensemble of future change experiments with CCSM3.0 has been very widely used by the community, and these runs are largely in response to a clear demand and need for a similar ensemble with the newer model.

The following table summarizes the Working Group Production requests.

Working Group	Production Request (kGAU)
Atmosphere Model Working Group	829.4
Biogeochemistry Working Group	1214.9
Chemistry Climate Working Group	883.5
Climate Change Working Group	1068.0
Climate Variability Working Group	1082.0
Land Ice Working Group	805.0
Land Model Working Group	427.0
Ocean Model Working Group	882.9
Paleoclimate Working Group	748.0
Polar Climate Working Group	974.1
Whole Atmosphere Working Group	1348.0
TOTAL	**10262.8**

Data Management

The key to the CESM data management plan is to have Production and Development data stored and distributed via different strategies, with each tailored to suit the different user needs. Furthermore, retention of data on the HPSS will be finite, so the capability will be developed to re-generate purged data if necessary. It can no longer be assumed that storage capacity will grow much faster than the data volumes. A designated data manager will be given the responsibility to implement the following plan.

a. Data Archiving

As part of this CSL proposal, each working group generated estimates of the data volume associated with each proposed development and production experiment (listed in the appendices). The following table summarizes the projected total for each working group:

Working Group	Development (Tbytes)	Production (Tbytes)
Atmosphere Model Working Group	19.2	19.5
Biogeochemistry Working Group	30.2	82.7
Chemistry Climate Working Group	18.7	17.6
Climate Change Working Group	0.0	38.6
Climate Variability Working Group	0.0	11.6
Land Ice Working Group	14.2	25.1
Land Model Working Group	19.9	56.4
Ocean Model Working Group	64.9	46.6
Paleoclimate Working Group	6.0	36.4
Polar Climate Working Group	23.4	29.4
Whole Atmosphere Working Group	35.0	67.9
TOTAL	**231.5**	**431.8**

The total data volume expected from both development and production activities is approximately 663 Tbytes. All data will be archived on the HPSS. The rate of data production is comparable to the current rate of data production. For example, as of November 1, 2010, the IPCC AR5 runs completed at NCAR over the previous year have accumulated to about 300 Tbytes. Thus, we proposed the following archival strategy:

Development: Output data will be stored on the HPSS for a period of 36 months after creation, at which point it will be removed, unless retention is requested from the relevant working group co-chairs.

Production: Output data will be stored on the HPSS for a period of four years. It will then be gradually cut back to 50% of its initial volume over a period of three additional years, based on usage and anticipated demand. This data level will be maintained for three more years. Afterward, each working group will determine what data are to be removed and at what rate, as the archived data is gradually reduced to an acceptable level, as determined by data archiving costs at the time.

b. Data Distribution:

Development: In general, output data will be made available only to the working group members that are directly involved in the experiments. For working group members that do not have access to the NCAR HPSS, these data will be made available via the ESG.

Production: Output data will be made available according to the guidelines established by the CESM data policy, which is formulated by the CESM SSC, NCAR and NSF. Initially, access is restricted to the working group members directly involved in the experiments. After a period of no more than 12 months after creation, these data will be made available to the community via the ESG.

Summary

Computer models are the most powerful tools for meeting the intellectual challenge of understanding the climate and the Earth system: they are the only scientific tool capable of integrating the myriad physical, chemical and biological processes that determine past, present and future climate. They are also essential for synthesizing, through data assimilation, diverse in-situ and remotely sensed observations, and they are the tools for testing and confirming understanding and for making predictions of use to society and policy makers.

For many years, NCAR has been at the forefront of international efforts to understand and predict the behavior of Earth's climate through the development and application of the CCSM and, more recently, the CESM. The development of this Earth Modeling System, moreover, is unique in that it occurs through strong partnership with scientists from universities, national laboratories, and other research organizations. The CESM enables the investigation of new scientific problems through partnerships with a community broader than ever before, and it is now enabling many new partnerships including those involved in adaptation and mitigation research.

The 2010 releases of CCSM4.0 and CESM1.0 were landmark events; however, testing, development and production simulations must continue along the overarching priorities identified in this proposal. High priority production simulations, for instance, include those that allow the CESM community to participate in coordinated international modeling activities as well as benchmark simulations to document CESM components and new coupled configurations of the model. It is requisite to understand the behavior of the various model configurations now possible under CESM1.0, including how new components interact with other components of the system. The development of next (interim) versions of CESM is already underway and is a focus of all working groups, including high resolution and new dynamical cores. Experiments are also being conducted to understand the source of biases in existing CMIP5 production simulations, as well as efforts to examine the impact of new physics that might further improve simulation fidelity.

The CSL computer resource remains indispensable in order to carry out this ambitious agenda. The objectives and priorities outlined in this proposal emanate directly from the community of scientists who participate in the CESM project through the 12 working groups and the CESM Scientific Steering Committee. They were developed, refined and prioritized after a several month process with the goal of producing a coherent and coordinated plan for the use of the CSL resource over the upcoming period of performance. The work outlined requires a total of 16,304.1 kGAU (6041.3 kGAU for development and 10262.8 kGAU for production simulations), or 1,086.9 kGAU per month, over the period April 2011 through June 2012. This request is necessary for the continued testing, development and application of CESM required to meet a wide variety of community needs and keep the project at the head of international modeling efforts.

Appendices

Atmosphere Model Working Group

1. Research Plan and Broad Overview Objectives

The goal of the Atmosphere Model Working Group is to provide a Community Atmosphere Model (CAM) as part of the Community Earth System Model (CESM) that integrates accurate physical, dynamical and biogeochemical representations of the earth's atmosphere and is capable of addressing cutting edge research problems relevant to the earth-system science community. The scope of these research problems is extensive; varying in time, space, scale, earth sub-system and application.

The primary research question remains the quantification of the anthropogenic forcing of the earth system through long-lived radiatively active greenhouse gases and the associated atmospheric feedbacks in response to increases in temperature. Predicting future states of the earth system requires an accurate representation of the interaction of the active physical, dynamical and chemical processes at scales relevant to policymaking needs. Assessments of potential future climate change impacts are hindered by a lack of detail and skill at regional scales (between 200 km and 10 km). Therefore, there is an urgent need to develop modeling predictions capable of providing this information. A demonstration of dynamical and physical process modeling fidelity, capability and efficiency at these scales is a necessary condition for providing such predictions.

The nature of the largest atmospheric uncertainty in the IPCC future predictions is the strength of the cloud-climate feedbacks that can lead to global and regional amplification of surface temperature changes. The coverage, elevation and condensed phase characteristics of clouds all have a role to play in these feedbacks and remain to be adequately assessed in models. Significant uncertainties also remain as to the indirect radiative effects of anthropogenic aerosols due to their impact on cloud formation, cloud properties and cloud lifetime. Investigation of these complex and intimately linked process interactions necessitates model calculations performed at or near the cloud scale and a capability to isolate and identify the most important interactions.

Unfavorable changes in local climate characteristics such as increases in extreme precipitation events, droughts and poor air quality events remain key metrics of the impact of climate change. Such changes are dependent on shifts in the hydrologic cycle, constituent transport processes and the nature of their interaction at these key scales about which much uncertainty remains. Short-term forecasts provide insight into these phenomena and demonstrate the predictive capability of the model in response to realistic initial conditions. This translates to an increased reliability for statistical estimates of changes to these phenomena in future climates.

Development Objectives

The Atmosphere Model Working Group will address the strategic, community and scientific objectives summarized in the Atmosphere Model Working Group Community Atmosphere Model (CAM) Strategic Plan. Specifically we are requesting resources to address the following development goals:

- Extending the capability for using CAM to investigate regional climate problems using globally high resolution simulations, global simulations with regional mesh refinement capability and limited area models
- Improving and harmonizing the representation of physical processes across resolved scales from global to mesoscale
- Understanding the interaction among the expanded representations of physical, chemical, radiative and dynamical processes
- Building on the capability provided in the CESM1.0 release with extensions to resolution, model dynamics and chemistry flexibility and interoperability

In order to maintain the cutting edge research capability in CAM we plan to lead model development with the aim of providing sufficient resolution and physical process fidelity to address regional climate problems across the globe and across scales. Computationally efficient techniques are needed to run CAM at resolutions approaching the horizontal near-cloud scale and hydrostatic limit of 10 km using unstructured grids that do not exhibit convergence of longitudinal grid points near the poles. Specifically, further development of the highly scalable High-Order Method Modeling Environment (HOMME) spectral element dynamical core will make it fully integrated into the coupled modeling system. Investigation of other candidate dynamical cores (including the Model for Prediction across Scales (MPAS) and finite volume on a cubed sphere (FV-CUBED) cores) is also planned. In parallel with these objectives we aim to develop and test the impact of techniques that specify sub-model grid atmospheric states that allow the representation of physical processes to act as close to cloud scale as possible.

We intend to extend the current CAM5 atmosphere in directions that provide greater flexibility as requested by the CESM community and that advance our understanding of the many ways the improved atmospheric processes interact in this new model version. Our highest priority is to complete, test and release a version of CAM5 that specifies aerosol burdens in the modal aerosol scheme (CAM5-PA). This will provide a significant reduction in computational cost, expected to be 50% of the current cost of CAM5, making its use more feasible for small university users and more comparable to running CAM4. This simplified model version will also prove invaluable for understanding the individual interactions among the aerosol, cloud, chemical, and radiation process that are difficult to disentangle in CAM5.

Supported CAM resolutions now span horizontal scales from 10s to 100s of kms while retaining the same physical packages and subject to only minor configuration differences. Efforts to move toward more scale-invariant parameterization across the wide range of available horizontal resolutions will focus on defining sub-grid distributions of atmospheric states that allow the scales of action to remain the same even if the resolved scales vary. As part of these ongoing efforts of evaluating and improving the model physics, we will implement the satellite observation simulator package (COSP) to allow direct comparison of model simulations against satellite-based observations such as from CloudSat, the International Satellite Cloud Climatology Project (ISCCP), the Multi-angle Imaging SpectroRadiometer (MISR) and The Moderate Resolution Imaging Spectroradiometer MODIS.

The modeling community has an ongoing requirement for a version of CAM and CESM that will efficiently run for many centuries or millennia and in many realizations in order to address science questions related to paleo-climate, complex physical system interactions and long time-scale variability in general. This also addresses associated development goals of the Paleo-Climate and Whole Atmosphere Working Groups. The Atmosphere Model Working Group would like to replace the existing low-resolution spectral-core based version of CAM with a competitive, computationally-viable version of CAM with the finite volume version of the dynamical core. This has many advantages associated with the Atmosphere Model Working Group supporting a more limited set of dynamical cores as well as the inherent superior transport properties that reside with the finite volume transport scheme.

Many scientific questions remain as to the benefit of lifting the model top of CAM and increasing the number of vertical layers. We plan to address these questions by lifting the upper boundary of CAM from around 2 mb (approximately the top of the stratosphere) to 0.01 mb (approximately the top of the mesosphere). The expected benefit of this change is to allow the zonal westerly jets to close correctly at the top of the model and remove the current requirement of closing the zonal jets through strong damping in high resolution simulations.

Performing experiments that are realistically initialized is crucial for demonstrating the predictive capability of the whole coupled system and for diagnosing the interactions among processes that lead to the drift toward known systematic climate simulation biases. We will perform a comprehensive set of short term (up to 20 days) initialized experiments in the Cloud-Associated Parameterization Framework (CAPT) in order to address the above predictive capability and nature of the climate drift. As an extension to this research we intend to add initialization to the ocean model with existing realistic ocean states derived from nudging or data-assimilation procedures performed as part of recent decadal prediction experiments with CESM1. Improved objective techniques with which to initialize the atmospheric state will further be investigated via the Data-Assimilation Research Testbed (DART).

Production Objectives

Community acceptance of new model configurations requires the provision of a number of standard experiments to compare with existing released configurations. The priorities are:

- Coupled climate validation with the HOMME dynamical core
- Climate validation using a prescribed aerosol capability in CAM5 (CAM5-PA)
- Coupled climate validation with the low resolution finite volume dynamical core
- Assessment experiments (including CFMIP and Transpose-AMIP)

The HOMME dynamical core was released with CCSM4 and CESM1, but not as a scientifically supported option. Enabling scientific support requires a significant number of long simulations in coupled configurations at equivalent resolutions to finite volume simulations in order to fairly compare with existing assessment-type simulations. In addition, new configurations that we hope to support in a scientific mode in the future will be similarly run in production experiments. This includes the prescribed aerosol version of CAM5 (CAM5-PA) and low horizontal resolution versions of CAM4 and CAM5 when they become available. Further experiments are also required as part of the Cloud-Feedback Model Intercomparison (CFMIP) and transpose-AMIP sub-projects of CMIP5. These are aimed specifically at addressing cloud feedback mechanisms and sensitivities of model biases to initialization and timescale.

2. Proposed Development and Computational Requirements

Development Experiments

a. Advancement of a scalable dynamical core for compatibility with atmospheric physics and coupled infrastructure

The inclusion of the spectral-element based HOMME dynamical core on a cubed sphere grid represents a very promising approach for providing much improved computational scalability compared to the poorer scaling finite volume or spectral dynamical cores. This is a high priority given that the next-generation NCAR computing facility is expected to have processor numbers of the order of 100,000 and the current finite volume dynamical core will be ill-suited to efficiently exploit a large number of these processors. We intend to investigate and document the climate characteristics of CAM-HOMME across a range of resolutions in order to complement existing DOE computational scaling activities. Shorter-term experiments will be performed at much higher resolutions to investigate and document the interaction of dynamics and parameterized physics at high resolution (nominally 0.2 deg/20 km). This will require a minimum of 10 years of CAM5-PA simulation in 2-year increments in order to provide sufficient sampling for interannual variability and annual climatological fields. The Atmosphere Model Working Group will work closely with the Chemistry-Climate Working Group and the Whole Atmosphere Working Group to investigate chemistry implementation in these high-resolution simulations.

b. A prescribed aerosol version of CAM5 (CAM5-PA)

The version of CAM5 released with CESM1 was developed using a prognostic version of the Modal Aerosol Model (MAM). This required an additional 20 species to be transported by the finite volume tracer advection scheme; representing a significant increase in computational overhead that approximately doubles the overall model cost. Furthermore, the inclusion of interactive aerosol in CAM5 and their new capability to directly influence size and number of in-cloud ice and liquid cloud particles introduces an extra degree of freedom. This makes it difficult to disentangle the cause-and-affect relationships of cloud aerosol interactions, particularly in future climate scenarios. We intend to develop a prescribed-aerosol version of CAM5 (CAM5-PA) that will provide a more comparable version to CAM4 both in terms of functionality and cost. This will require a number of development experiments initially at low resolution (50 years of 2-year tuning experiments at 1.9x2.5) and a limited number of higher resolution verification experiments (20 years of 2-year experiments at 0.9x1.25).

c. Development of sub-grid scale atmospheric column states

In moving towards implementing the moist physics on sub-grid scale thermodynamic states we will require a number of CAM5-PA integrations to test the implementation strategy. This will involve development of algorithms to generate sub-grid vertical profiles from the individual or near-neighbor groups of resolved grid states based on assumed PDFs of water species; generally referred to as 'subcolumns'. Initial parameterization interactions with the sub-columns will begin with the microphysics and extend to the radiation and convection schemes. A conservative estimate over the course of the development period for a sub-column capable version of CAM5-PA (CAM-SC) will entail a model cost of approximately two times that of the standard CAM5-PA. For rapid progress a 1.9x2.5 configuration with 50 years of 2-year simulations will be performed.

d. Implementation experiments for SP-CAM

The super-parameterized version of CAM (CAM-SP) embeds a cloud resolving model (CRM) that occupies a limited area of each CAM grid column and replaces the majority of the standard parameterized physics. The Atmosphere Model Working Group in collaboration with the Software Engineering Working Group will implement an existing version of CAM-SP into the CESM modeling framework with the intention of supporting this method of running the model in future CESM releases. The implementation of CAM-SP will be built off the updated data structures from the sub-column development. It will therefore require a more limited set of development experiments totaling 5 years of 1-year, 1.9x2.5 CAM standalone experiments which, due to the high cost of CAM5-SP, are estimated to be approximately 150 times that of CAM5-PA.

e. CAM5 climate validation and climate improvements

Since CAM5 is a relative new model a number of tasks remain that will address shortcomings in the existing climate simulations and identify characteristics and shortcomings in the model beyond just the mean climate simulation. Significant mean biases to be investigated and addressed include, weak clearsky long-wave radiative forcing, low in-cloud water concentrations, strong cloud aerosol interactions and radiative effects. In addition, long outstanding coupled biases such as the double ITCZ, excessive tropical water cycle and variable cloud-feedbacks during ENSO will required a significant number of model simulations. The intention is to address these biases using moderate resolution versions of CAM5-PA with 100 years of 1.9x2.5, 2-year experiments and 100 years of 20-year, coupled 1.9x2.5_gx1 CESM1(CAM5).

f. Physical parameterization development improvement and development

The core research activity of the Atmosphere Model Working Group continues to be the development of new and more accurate physical representations of atmospheric processes. Experiments will be performed to facilitate a variety of parameterization improvements. These include combining the shallow and deep convection schemes to provide a unified convection capability, the extension of the existing shallow UW convection parameterization to perform deep convection, the extension of the existing Morrison-Gettelman microphysics scheme to more realistically represent microphysical processes in deep convection and implementing the turbulent mountain stress scheme in a more robust and resolution invariant manner. This will require the equivalent of 50 years of 2-year, 1.9x2.5 and 50 years of 2-year, 0.9x1.25 CAM5-PA simulations.

g. Extensions to CAM resolution and domain representation

To extend CAM capability we will perform experiments that integrate CAM with a low resolution version of the finite volume dynamical core. This atmosphere model is intended to be a replacement for the atmosphere model used in the CCSM4 spectral Eulerian T31_gx3 coupled model which remains the main research tool for the Polar Climate Working Group and for the 4x5 low-resolution Whole Atmosphere Community Climate Model (WACCM) used by the Whole Atmosphere Working Group. We will require 20 years of 2-year, 2.5x3.3 simulations for each of CAM4 and CAM5-PA atmospheric physics. In addition, the sensitivity to vertical resolution in CAM remains poorly understood. To address this we will pursue two lines of research: elevating the upper boundary (model top) in CAM to fully encompass the stratosphere and increasing the number of vertical levels up to a doubling of the current CAM5 resolution (60 levels). Initial exploration will require the equivalent of 50 years of 2-year simulations with a linear increase in cost equivalent to a doubling of the CAM5-PA, 1.9x2.5 standard configuration cost. The Atmosphere Model Working Group will seek guidance from existing high-topped atmosphere models supported by the Whole-Atmosphere Working Group to determine optimal placement of additional vertical levels.

h. Short-term forecast experiments

The scientific motivation to test and demonstrate the capability of CAM in forecast mode continues to grow, both in terms of understanding the inherent short term predictability (days to weeks) of the system and for investigating the systematic bias and drift to this bias seen in CAM climate simulations. Therefore, we propose to perform a series of CAM experiments at a range of resolutions to investigate the prediction capability of tropical cyclones (requiring high horizontal resolutions) and the Madden Julian Oscillation (requiring both low and high resolution configurations) using the CAPT framework. To understand the ocean's role in this short term prediction we intend to perform fully coupled versions of the above experiments using existing initialized ocean/ice provided from ongoing decadal prediction activities within the CGD. Methods to identify the sources of model error through data assimilation will also continue through the DART ensembles of short term experiments. This research will require the equivalent of 30 years each of CAM5-PA 0.9x1.25 and CESM (CAM5-PA) simulations. For high resolution experiments we will perform 10 years each of CAM5-PA 0.23x0.31 and CESM1 (CAM5-PA) 0.23x0.31_gx1.

Experiment	Model Config	# of runs	# of years	GAU / year	Total KGAU	Total Data Volume (Gb)
CAM5 HOMME High resolution AMIP	ne120np4_0.23x0.31/L30 HOMME	5	2	12,300	123	2,500
CAM5-PA+ Prescribed aerosols AMIP	1.9x2.5/L30,FV 0.9x1.25/L30,FV	25 10	2 2	191 768	9.6 15.4	160 248
CAM5-SC+ Sub-columns AMIP	1.9x2.5/L30,FV	2	25	1536	76.8	160
CAM5-SP+ Super-parameterization (64 CRM columns of data per grid box) AMIP	1.9x2.5/L30,FV	1	5	28,650	143.3	1024
CAM5-PA+ Bias reductions AMIP, coupled	1.9x2.5/L30 0.9x1.25_gx1/L30	50 5	2 20	191 1,163	19.1 116.3	320 2,640
CAM5-PA+ Parameterization development AMIP	1.9x2.5/L30 0.9x1.25/L30	25 25	2 2	191 768	9.6 38.4	160 620
CAM4/5 Resolution and domain expansion AMIP	CAM4, 2.5x3.33/L26 CAM5-PA+, 2.5x3.3/L30 CAM5-PA+, 1.9x2.5/L60	10 10 25	2 2 2	42 107 382	0.8 2.1 19.1	12 35 320
CAM5-PA+ Short term forecasts AMIP, Coupled (100% data o/head)	0.9x1.25/L30 0.9x1.25_gx1/L30 0.23x0.33/L30 0.23x0.33_gx1/L30	30 30 10 10	1 1 1 1	768 1,163 12,300 14,000	23.4 34.9 123.0 140.0	744 1,584 3,968 4,280
TOTAL					**894.8**	**19,200**

+Experimental model configurations for which GAU costs are estimates.

Production Experiments

a. Validation of CAM-HOMME coupled climate

The climate of the lower resolution version of CAM-HOMME (resolution nominally 1 deg/80 km) requires significant documentation to identify similarities and differences with the standard production FV-core CAM4 simulations. We intend to perform fully coupled experiments initially using CAM4 physics which will require 356 simulation years for a pre-industrial control and 20th century all-forcings experiment.

b. Validation of CAM5-PA coupled climate

The final version of a prescribed aerosol version of CAM5 (CAM5-PA) may have different mean climate and variability characteristics in a coupled climate configuration. Therefore, experiments to validate the coupled climate including a pre-industrial control and 20th century all-forcings simulation will require 356 years of simulation at 0.9x1.25_gx1.

c. Validation of CAM4 and CAM5 coupled climates at low-resolution

To enable the low-resolution version of CAM using the finite volume dynamical to become the standard supported version along control coupled integration is required. Given the use of CAM4 physics in the current supported low-resolution version of CAM at T31 it is necessary to perform coupled integrations using both CAM4 and CAM5 physics at 2.5x3.33_gx3 resolutions for a single 200-year period in each case.

d. Assessment experiments for CFMIP

Outstanding requests from the Coupled Model Intercomparison Project (CMIP5) include simulations specified by the international CFMIP sub-project. Some of the experiments are re-runs of existing CMIP5 experiments that require additional specialized diagnostics including the COSP satellite simulating package, which takes high-temporal resolution output for some of the simulations and emulates the flight of satellites through the model domain. Other required experiments that the Atmosphere Model Working Group will focus on use specialized configurations such as aqua-planet, all-ocean domains and sensitivity experiments where sea surface temperatures are prescribed as present-day, but with CO_2 levels set to 2x or 4x present-day values. There is expected to be of order 100 years of CAM4 simulation at 0.9x1.25 to fulfill the majority of the CFMIP experiment requirements for CCSM4.

e. Assessment experiments for Transpose-AMIP

Transpose-AMIP is a WMO Working Group on Numerical Experiments (WGNE) and Working Group on Coupled Models (WGCM) endorsed activity to run climate models in weather-forecast mode. A number of global hindcasts are to be produced with CAM4 and CAM5-PA, each hindcast being 5 days in length for 16 hindcasts separated by 30 hour intervals during 4 periods: October 2008, January 2009, April 2009 and July 2009. This ensures sampling throughout the annual and diurnal cycles for each gridpoint for a given lead time. These periods have been chosen to tie in with the Year of Tropical Convection (YOTC) and various other relevant IOPs. Model state variables are to be initialized from ECMWF YOTC analyses for the first set of experiments. In order to test the sensitivity of the results to the choice of analysis the set of experiments will be repeated using the NASA/GMAO Modern Era Retrospectiveanalysis for Research and Applications (MERRA). The total run time for each ensemble set is of order 1 year per analysis choice. The Atmosphere Model Working Group will perform this analysis using 0.9x1.25 and 0.23x0.31 resolutions for both CAM4 and CAM5. The significant volume of high frequency output in the data requirements will increase the standard run-time by an estimated factor of 2.

Experiment	Model Config	# of runs	# of years	GAU / year	Total KGAU	Total Data Volume (Gb)
CAM4 HOMME Climate validation Coupled	ne30np4_0.9x1.25_gx1/L26, HOMME	2	200/156	666.6	237.3	7,081
CAM5-PA+ Climate Validation Coupled	0.9x1.25_gx1/L30	2	200/156	1,163	414.0	9,400
CAM4/CAM5-PA+ Low resolution Climate Validation Coupled	CAM4, 2.5x3.33_gx3/L26 CAM5-PA+, 2.5x3.3_gx3/L30	1 1	200 200	100 170	20.0 34.0	420 640
CAM4 CFMIP experiments AMIP (100% data a/head)	0.9x1.25/L26	10	10	401	40.1	860
CAM Transpose AMIP AMIP (100% data overhead)	CAM4, 0.9x1.25/L26 CAM5-PA+, 0.9x1.25/L30 CAM4, 0.23x0.31/L26 CAM5-PA+, 0.23x0.31/L30	128 128 128 128	5days 5days 5days 5days	401 768 7,500 12,300	1.6 3.2 30.0 49.2	17 50 276 792
TOTAL					**829.4**	**19,500**

+Experimental model configurations for which GAU costs are estimates.

Biogeochemistry Working Group

1. Research Plan and Broad Overview of Objectives

The goal of the biogeochemistry working group is to produce a state-of-the-art earth system model for the research community that includes terrestrial and marine ecosystem biogeochemistry. This model will be used to explore ecosystem and biogeochemical dynamics and feedbacks in the earth system. Land and ocean ecosystems 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 CO_2 growth, produce a rich array of climate forcings and feedbacks that amplify or diminish climate change. Biota 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-ecosystem interactions (and in some cases even the sign) are not well constrained, and are critical scientific unknowns affecting the skill of future climate projections.

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. While the magnitude of contemporary ocean uptake of anthropogenic carbon is constrained by observations to within 10%, the future uptake is uncertain. For example, while there is consensus that global warming will decrease the efficiency of ocean uptake, the magnitude of this affect is poorly constrained. A primary objective of the Biogeochemistry Working Group is to estimate this future ocean uptake using CESM.

Current research suggests that terrestrial ecosystems are at present a net carbon sink, but this conclusion masks considerable complexity and uncertainty with respect to future behavior. The availability of nitrogen, as well as other nutrients (e.g., phosphorus), alters the magnitude, and possibly the sign, of the carbon cycle-climate feedback. Additional processes associated with ozone deposition and methane emission will alter the magnitude of the biogeochemical-climate feedbacks. Human activities from land use and land cover change play a very direct role in terrestrial ecosystem dynamics. 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. Another primary objective of the Biogemchemistry Working Group is to analyze these, and other, terrestrial feedbacks using CESM.

Development Objectives

Better understanding of ecosystem and biogeochemical dynamics and feedbacks with respect to a changing climate requires an expansion of current CESM land and ocean model capabilities.
Biogeochemistry development is focused on: improving our simulations of the global carbon cycle; introducing more interactions between the carbon cycle, other biogeochemical cycles (e.g., nitrogen, phosphorus, and mineral aerosols), and ecosystem processes (e.g., land use, wildfire, and ocean acidification); introducing more biogeochemical interactions with other CESM component models (e.g., atmospheric chemistry); understanding how biases in the climate simulation impact biogeochemical cycles; and continuing research into techniques to spin up biogeochemical tracers in the ocean.

We are requesting computing resources to address the following overarching development goals:

- Understanding the causes of key biases in the CESM1 simulation of the terrestrial carbon cycle; and developing and evaluating new parameterizations to improve model simulations
- Evaluate the impact of physical ocean model developments on biogeochemical biases
- Continue development of techniques to efficiently spin up biogeochemical tracers in the ocean
- Improve the representation of aspects of ocean biogeochemical parameterizations related to ocean acidification and the closely related alkalinity cycle

The land carbon cycle model requires further development and evaluation to become a state-of-the-art community modeling resource. Emphasis is on development and evaluation of the present-day carbon cycle, its interactions with nitrogen, its modification from disturbances by wildfire and land use, and the overall carbon cycle feedback in the climate system. Additionally, analyses of CESM1 carbon cycle simulations reveal significant biases in terrestrial gross primary production, leaf area index, vegetation and soil carbon stocks, and soil carbon turnover. These biases need to be addressed through continued development of the leaf phenology, carbon allocation, litterfall, soil biogeochemistry, and nitrogen cycles in CLM. The Land Model

Working Group is addressing these developments in its computing allocation, and here we test these developments in carbon cycle simulations.

Notable biases and deficiencies of marine biogeochemical aspects of CESM1 simulations include: underestimation of the contemporary ocean uptake of anthropogenic carbon, excessively large oxygen minimum zones (OMZs), lack of feedback of ocean acidification onto biogeochemical processes, and an incomplete representation of the alkalinity cycle. A physical process that plays a key role for the first two biases is ventilation of the ocean interior. This process is being studied by a NOAA/NSF funded Climate Process Team (CPT), which is seeking computational resources independently of this CSL proposal. We are requesting computational resources to evaluate the impact of developments from that effort on the OMZ problem. Evaluating the impact of developments on ocean uptake of anthropogenic carbon currently requires lengthy simulations, which becomes impractical when multiple developments are being evaluated. Thus, we are allocating a portion of our computational request on the continued development of techniques to efficiently spin up biogeochemical tracers. These techniques would ease the evaluation of impacts of developments on ocean carbon uptake. Such a technique would also enable us to study long-term behavior of modifications to biogeochemical parameterizations. As the ocean takes up carbon from the atmosphere, pH levels will decrease, pushing the ocean towards an acidic state. This change in chemistry alters biogeochemical cycles, and we are requesting resources to include these effects in our biogeochemical parameterizations. We will also put effort into enhancing the representation of the alkalinity cycle of the ocean, which plays a key role in determining pH levels.

Production Objectives

Production runs address fully coupled carbon cycle simulations. We are requesting computing resources to address the following overarching production goals:

- Additional CMIP5 fully coupled carbon cycle simulations to address specific biogeochemical and biogeophysical earth system feedbacks associated with land cover change
- Evaluate biogeochemical cycles and feedbacks in a less costly lower resolution version of the coupled model
- Evaluation of carbon cycle model developments in fully coupled carbon cycle simulations

The current on-going CESM1 simulations for CMIP5 include transient land cover change. This land cover change affects climate by altering surface albedo and evapotranspiration (biogeophysical feedback) and by altering the carbon cycle (biogeochemical feedback). 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. Land cover change releases carbon to the atmosphere with deforestation (positive climate forcing), but stores carbon (negative climate forcing) with reforestation. The net global biogeochemical forcing is positive (a global release of carbon). The extent to which biogeophysical processes may offset this biogeochemical warming is under considerable scientific debate. We propose a set of fully coupled CESM1 carbon cycle simulations that build upon previous CMIP5 simulations to address this issue.

When biogeochemical parameterizations are active, the fully coupled model of CESM is an expensive model to run. This makes development work fairly burdensome, particularly for university collaborators. We will benchmarks parameterizations in a less costly lower resolution version of CESM, so that development can proceed in a less costly manner.

In final set of simulations, we propose fully coupled carbon cycle simulations to address the impact of land and ocean model developments on carbon cycle-climate coupling.

2. Proposed Experiments and Computational Requirements

Development Experiments

a. GCP/TRENDY

The IGBP Global Carbon Project (GCP) (http://www.globalcarbonproject.org/index.htm) and the TRENDY terrestrial carbon cycle model intercomparison (http://dgvm.ceh.ac.uk/) are important international community modeling activities. GCP includes estimates from numerous terrestrial models in its annual carbon budget analysis. TRENDY is a community-driven intercomparison of terrestrial carbon cycle models. Both projects have become a standard benchmark for terrestrial carbon model evaluation. They rely on offline transient simulations of the terrestrial carbon cycle, forced with historical atmospheric CO_2, climate, land cover change, and other forcings (e.g., nitrogen deposition) over the period 1860-2009. TRENDY additionally requires a second simulation to quantify the CO_2 fertilization effect. CLM4 is currently participating in both activities.

We propose additional GCP/TRENDY simulations that compare new CLM developments to the benchmarked CLM4. The TRENDY protocol requires two 150-year simulations (1860-2009, one with all forcings, and one with CO_2 only) at 0.5° resolution for a total of 300 simulation years. We estimate an additional 300 years is required for model spinup. We anticipate two such sets of simulations to address various model developments.

b. Methane

In collaboration with the Land Model Working Group and chemistry/climate working, the Biogeochemistry Working Groupis developing and testing a new methane emission parameterization for wetlands and rice paddies. The simulations so far have been land-only simulations. For this CSL proposal, we plant to test the methane model in the atmosphere, based on simulations for the time period 1980-2010, and verify that the model can reproduce observed fluctuations in atmospheric methane, using best available information about other sources of methane. In order to conduct these comparisons, we will need to use the offline atmospheric chemistry model, at the 2x2 resolution, using an intermediate complexity chemical scheme (500 GAUs per year).

c. Evaluation of Ocean Physical Parameterization development on OMZs

We propose a handful of multi-decadal runs to evaluate the impact of ocean ventilation developments on the extent of the OMZs. Preliminary examination of the time evolution of the OMZs reveals that a significant amount of the excessive extent is established within a few decades of a run that has been initialized with observed oxygen. So runs of length 50 years are sufficient for these evaluation purposes. We will rely on the spinup technique mentioned above and described below to examine OMZ behavior on longer timescales.

d. Efficient ocean spinup technique development and gx3v7 spinup

A continuing issue for development work and initialization of coupled simulations is the computational cost of long evaluation and spinup runs. Because of the long timescales of ocean circulation, the ocean does not equilibriate unless run for thousands of years. We propose experiments to continue development of a Newton-Krylov (NK) solver that efficiently generates equilibrium tracer distributions, thereby eliminating the need for such lengthy integrations. Loosely speaking, the solver constructs an optimal linear combination of perturbations to the initial conditions by evaluating how balanced the tracer distributions are when individual perturbations are added. So in practice, the solver requires numerous short integrations. These integrations include additional diagnostic tracers making them more expensive than typical CECO integrations. Note that it is not necessary to archive output from each individual perturbation experiments. Variations of the solver will be evaluated with the less costly gx3v7 model, and then run in the gx1v6 model. A long control run will be performed with the gx3v7 model to validate the fast solver at that resolution. The application of the solver at gx1v6 will be validated by verifying that model doesn’t drift when initialized with the generated solution.

e. Ocean acidification and alkalinity cycle development

A topic that is of current interest to the ocean biogeochemical research community is ocean acidification. We are proposing development work to make CESM1 a better tool to study this problem than it currently is. Development work will focus on including the effect of predicted ocean pH level on biogeochemical fluxes and enhancing the representation of the alkalinity cycle by including another calcifying functional group to the ocean model. Due to the cost of the gx1v6 resolution model, the majority of this work will be performed with the gx3v7 resolution model.

Experiment	Model Config	# of runs	# of years	GAU / year	Total KGAU	Total Data Volume (Gb)
GCP/TRENDY 1860 spinup	ICN, 0.47x0.63	2	300	120	72	2,700
GCP/Trendy 1860-2009	ICN, 0.47x0.63	2	150	120	36	1,350
Methane	Offline atmospheric chemistry, 2x2	2	30	500	30	2,100
OMZ Evaluation	CECO, gx1v6	5	50	323	80.75	7,525
Ocean gx3v7 spinup	CECO, gx3v7	1	2,000	17	34	7,000
Newton-Krylov	CECO+, gx3v7 CECO+, gx1v6	500 200	1 1	34 600	17 120	0 0
Ocean acidification, alkalinity cycle	CECO, gx3v7 CECO, gx1v6	20 4	50 50	17 323	17 64.6	3,500 6,020
TOTAL					**471.35**	**30,195**

Production Experiments

a. Land cover change

We propose two fully coupled CESM1 carbon cycle simulations to address the role of land cover change in climate simulations. One experiment will allow only the biogeophysical effects of land cover change; the second experiment will allow only the biogeochemical effects. These experiments will cover the period 1850-2100 and will match an existing CESM1 simulation that includes both processes. The three experiments will allow us to quantify the biogeophysical land cover change forcing, the biogeochemical forcing, and their interactions.

b. Low-resolution benchmark runs

Because of the expense of the fully coupled model, with active biogeochemical parameterizations, it is important to have a less costly version of the model for development work. We propose running baseline coupled simulations, control and transients, that can be used to evaluate development. This will require a spinup of the ocean biogeochemical tracers, with coupled model forcing, a coupled control, and transient simulations.

c. Coupled model evaluation runs

We propose a pair of coupled carbon cycle simulations to evaluate the impact of land and ocean model developments (initially evaluated through uncoupled simulations) on carbon cycle-climate coupling. We anticipate that the new developments will alter the global carbon balance, so we are proposing a control run, that will probably have a drifting carbon cycle, and a transient run, spanning 1850-2100, using RCP8.5 emissions.

Experiment	Model Config	# of runs	# of years	GAU / year	Total KGAU	Total Data Volume (Gb)
Land cover change	BGC, 0.9x1.25_gx1v6	2	250	1022	511	38,150
Ocean spinup, gx3v7 Coupled forcing	CECO, gx3v7	1	1,000	17	17	3,500
Low-res Coupled control	BGC,T31_gx3v7	1	1,000	60	60	3,800
Low-res Coupled transients	BGC, T31_gx3v7	6	250	60	90	9,150
Coupled Model Evaluation Control	BGC, 0.9x1.25_gx1v6	1	300	938	281.4	9,030
Coupled Model Evaluation Transient	BGC, 0.9x1.25_gx1v6	1	250	1,022	255.5	19,075
TOTAL					**1,214.9**	**82,705**

Chemistry Climate Working Group

1. Research Plan and Broad Overview of Objectives

The goal of the Chemistry-Climate Working Group is to continue the development of the representation of chemistry in the CESM and to further our understanding of the interactions between chemistry and climate. The scientific motivations lie in the understanding of present-day and future air quality, understanding the role of climate change on composition and changes in lower stratospheric ozone. In particular, the use of CAM-chem (i.e. the version of CAM4 with interactive chemistry) for the definition of atmospheric composition in the CCSM4 simulations for IPCC AR5 requires additional sensitivity studies and testing for full comprehension. We also have to answer new requests from the community on understanding geo-engineering. Finally, new model configurations (high resolution, HOMME dynamical core, CAM5 physics, …) are likely to push our representation of chemistry in uncharted territories and we will validate these new simulations. These three main axes define the main research objectives of the Chemistry-Climate Working Group over the duration of this CSL proposal.

Development Objectives

The representation of chemistry in CESM needs to be tested and evaluated in existing and forthcoming CAM configurations. These configurations are:

- CAM5 physics, especially the coupling of interactive gas-phase chemistry and the modal aerosols and the impact of the new planetary-boundary layer,
- High-resolution (up to 0.25°) and new dynamical cores (such as HOMME and possibly MPAS), testing convergence of chemical fields over the full range of resolutions,

- The extension of the CAM model top to contain the whole stratosphere, following the MACCM framework developed as a precursor to WACCM, to capture the main regions of coupling between the troposphere and the stratosphere; this is done in collaboration with the Atmosphere Model Working Group, and our focus will be on the chemistry simulations in MACCM. In all cases, extensive comparison with observations will be conducted to identify possible improvements from these new configurations. In addition, small efforts related to development of aerosol modeling and data assimilation are included.

  The second major objective is related to the recent development in the understanding and the modeling capabilities for new chemistry, mainly isoprene oxidation and halogen. Both aspects are significant players in determining tropospheric ozone and methane lifetime, especially considering their mainly biological origins, which are strongly affected by climate change. It is expected that this additional chemistry will help reduce existing biases in tropospheric OH (the main sink for methane). Additional computer time is requested for refinement and development of the representation of deposition processes (wet and dry).

Production objectives

CAM-chem was used extensively to perform 1850-2100 (all RCPs) simulations to define atmospheric composition (and deposition fields) for use in CCSM4. These results now require additional simulations for a full understanding of what is driving the simulated changes. In particular, it is important to understand the specific role of climate versus emissions. For that purpose, following a procedure we have used very successfully in the recent past, we are proposing to perform simulations (1850-2005) in which one key element (anthropogenic emissions for example) are kept at their 1850 values. The combination of those experiments will define the history and amplitude of the role of each driving force. In addition, in support of the Atmospheric Chemistry and Climate initiative, we will perform hindcast simulations of tropospheric and stratospheric composition for comparison with the observational record (1980-present). These simulations will be done in collaboration with P. Hess (Cornell University).

In support of IPCC AR5, there is also a growing interest in geoengineering. In particular, A. Robock (Rutgers University) is leading an international effort to intercompare model simulations related to solar radiation reduction and input of sulfur in the lower stratosphere. Complementary to simulations proposed by the Climate Change Working Group and by P. Rasch (PNNL), we are proposing to perform a suite of simulations in which the release of sulfur is studied in CAM-chem using CAM4 physics (i.e. no aerosol indirect effect). In addition, we are proposing to perform one decadal prediction experiment with interactive chemistry. The goal of this simulation is to study potential changes in air quality within the next few decades. Furthermore, we are proposing to dynamically downscale (using the chemistry version of the Nested Regional Climate Model, NRCM) such mid-century projections to represent regional and sub-regional air quality in more details, with resolution on the order of 10 km.

Further resources are requested for the additional study of nitrogen deposition (an important input to the CLM-CN model) in collaboration with C. Heald (Colorado State University).

2. Proposed Experiments and Computational Requirements

Development Experiments

a. Chemistry in CAM5

The representation of aerosols (modal Scheme MAM3) In CAM5 has relied so far on using existing pre-computed distributions of oxidants (such as ozone and hydrogen peroxide). We propose to perform simulations in which the modal aerosols are interacting with gas-phase chemistry. For that purpose, we will use the tropospheric chemistry mechanism "trop_mozart" (96 tracers) as this provides the most comprehensive representation of chemistry. In addition, we will be able to analyze the impact on chemistry of the new physics parameterizations (such as the PBL scheme) of CAM5. In particular, we intend to perform side-by-side simulations with CAM4 and CAM5 physics, everything else being equal to identify differences.

- 4x10-yr Simulation 1.9°x2.5° F-case CAM5 w/ trop_mozart@550 GAU/yr
- 4x10-yr Simulation 1.9°x2.5° F-case CAM4 w/ trop_mozart@360 GAU/yr

b. High-resolution and new dynamical cores

We will perform CAM-chem Simulations with high (0.5° and 0.25°) resolutions to identify potential problems, convergence and identify areas of improvement against observations. Such simulations can also be compared to the specified-dynamics version of CAM-chem forced by the GMAO GEOS-5 meteorological analysis at their original resolution of 0.5° by 0.625° and coarser, to specifically evaluate the changes with resolution of chemistry only. In addition, we will be testing chemistry within the HOMME (and possibly MPAS) dynamical core. These tests will be performed using the stratospheric-tropospheric chemistry version of CAM-chem ("reduced chemistry," 82 tracers) to fully document the model behavior in those regions of the atmosphere.

- 20-yr Simulation 1.9°x2.5° F-case CAM4 w/ reduced chemistry @360 GAU/yr
- 20-yr Simulation 0.9°x1.25° F-case CAM4 w/ reduced chemistry @1400 GAU/yr
- 20-yr Simulation 0.47°x0.63° F-case CAM4 w/ reduced chemistry @5600 GAU/yr
- 20-yr Simulation 1.9°x2.5° F-case CAM4-HOMME w/ reduced chemistry @300 GAU/yr
- 20-yr Simulation 0.9°x1.25° F-case CAM4-HOMME w/ reduced chemistry @1120 GAU/yr
- 20-yr Simulation 0.47°x0.63° F-case CAM4-HOMME w/ reduced chemistry @4480 GAU/yr

c. MACCM

In collaboration with J. Bacmeister, J. Richter, and other members of the Atmosphere Model Working Group, we are proposing simulations to further the development of chemistry in MACCM. This model will provide a missing bridge between the low-top (40 km) CAM and the high-top (140 km) WACCM. Proposed Simulations will focus on the interaction between dynamics and chemistry in the stratosphere and will focus on the ability to represent the variability and seasonal cycle of stratospheric ozone.

- Tuning of MACCM dynamics through the evaluation of stratospheric chemistry: 10x5-yr Simulations 1.9°x2.5° F-case MACCM (52L) w/ WACCM chemistry@750 GAU/yr

d. CARMA

CARMA (University of Colorado/NASA-Ames Community Aerosol and Radiation Model for Atmospheres, Toon et al., 1988) is an aerosol model based on a bin-resolved representation of the size distribution (instead of pre-defined modes as in MAM). This has the advantage of providing a more comprehensive representation of the impact of physics and chemistry on the aerosol size distribution. This model is being applied to a variety of research topics (troposphere and stratosphere) and we propose here simulations (in collaboration with B. Toon's Group at CU) to explore the model capabilities in CAM-chem. All simulations with 1.9°x2.5° F-case CAM4 w/CARMA@500 GAU/yr

- Sea-salt: 25-yr simulation
- PSCs: 25-yr simulation
- Combustion aerosols: 10-yr simulation
- Forest fires: 10-yr simulation
- Early-earth studies: 20-yr simulation
- Lower Stratosphere sulfate: 10-yr simulation

e. Data assimilation

This is a continuation of the work on assimilating satellite observations of chemical species in CAM-chem using the IMAGE DART framework. This systematic assimilation (carbon Monoxide from MOPITT, Measurements Of Pollutants In The Troposphere) will help us diagnose systematic errors in the representation of chemistry in CAM-chem.

- Impact of aerosols assimilation: 2 X 40-member X 1-yr Simulations 1.9°x2.5° F-case CAM4 w/ trop_mozart@360 GAU/yr

Total: 28,800 GAU, output: 0.96 Tb

f. Isoprene

Recent field experiments and theoretical studies have indicated that our representation of isoprene chemistry as represented in the current generation of models is inaccurate, possibly even in the sign of the impact of isoprene emissions on OH chemistry, especially in non-polluted boundary layers. This can impact the lifetime of longer-lived species, such as methane and carbon monoxide, both ozone precursors. In addition, isoprene is now recognized as a key precursor to organic aerosol, with mechanistic understanding evolving rapidly. We intend to perform a systematic analysis of the various proposed isoprene chemistry mechanisms and compare with observations (including secondary-organic aerosols). In addition, we will update our representation of volatile organic compounds in CLM.

- New mechanisms: 5x10-yr Simulations 1.9°x2.5° F-case CAM4 w/ trop_mozart@360 GAU/yr
- Emissions: 10-yr Simulation 1.9°x2.5° F-case CAM4 w/ trop_mozart@360 GAU/yr

- Methane Lifetime (present And future conditions): 5x20-yr Simulations 1.9°x2.5° F-case CAM4 w/ trop_mozart@360 GAU/yr

g. Halogen chemistry

Halogen (Cl, Br, and I) chemistry is of importance for stratospheric ozone. In addition, our recent work is showing the importance of short-lived halogen (emitted by biogenic activity in the ocean) chemistry on ozone throughout the troposphere. We propose to expand this analysis and study the impact on lower-stratospheric ozone of those short-lived tropospheric compounds. This will be done in conjunction with further studies to improve the representation of stratospheric chemistry in CAM-chem, as some shortcomings (mainly the amplitude of the Antarctic Ozone hole) were identified in the recent WMO report.

- Tropospheric short-lived halogens (sensitivity to emissions and chemistry): 20x2-yr simulations1.9°x2.5° F-case CAM4 w/ extended trop_mozart@500 GAU/yr
- Stratospheric Ozone in CAM-chem (correction of biases through tuning of biases, transport and chemistry): 20x5-yr Simulations 1.9°x2.5° F-case CAM4 w/ reduced chemistry@360 GAU/yr

h. New parameterizations

The representation of wet and dry deposition in CAM-chem needs to be updated to better reflect recent observations; for example, nitric acid tends to be strongly underestimated in the upper troposphere. Simulations will be performed to update such representation and compare with observations from field campaigns. Additional simulations will be performed to test and update additional processes associated with chemistry such as emissions, photolysis, etc.

- Sensitivity simulations to compare developments in processes against available observations: 25x2-yr Simulations 1.9°x2.5° F-case CAM4 w/ trop_mozart@360 GAU/yr

Experiment	**Model Config**	**# of runs**	**# of years**	**GAU / year**	**Total KGAU**	**Total Data Volume (Gb)**
Chemistry in CAM5	1.9°x2.5° F-case CAM5 w/trop_mozart	4	10	550	22.0	1,080
	1.9°x2.5° F-case CAM4 w/trop_mozart	4	10	360	14.4	
High-resolution and new dynamical cores	1.9°x2.5° F-case CAM4 w/trop_mozart	1	20	360	7.2	10,400
	0.9°x1.25° F-case CAM4 w/trop_mozart	1	20	1,400	28.0	
	0.47°x0.63° F-case CAM4 w/trop_mozart	1	20	5,600	11.2	
	1.9°x2.5° F-case CAM4-HOMME w/trop_mozart	1	20	300	6.0	
	0.9°x1.25° F-case CAM4-HOMME w/trop_mozart	1	20	1,120	22.4	
	0.47°x0.63° F-case CAM4-HOMME w/trop_mozart	1	5	4,480	89.6	
MACCM	1.9°x2.5° F-case MACCM (52L) w/WACCM chemistry	10	5	750	37.5	1,000
CARMA	1.9°x2.5° F-case CAM4 w/CARMA	1	25	500	12.5	1,000
		1	25	500	12.5	
		1	10	500	5.0	
		1	10	500	5.0	
		1	20	500	10.0	
		1	10	500	5.0	
Data Assimilation	1.9°x2.5° F-case CAM4 w/trop_mozart	80	1	360	28.8	960
Isoprene	1.9°x2.5° F-case CAM4 w/trop_mozart	5	10	360	18.0	1,920
		10	1	360	3.6	
		5	20	360	36.0	
Halogen chemistry	1.9°x2.5° F-case CAM4 w/extended trop_mozart	20	2	500	20.0	1,760
	1.9°x2.5° F-case CAM4 w/reduced chemistry	20	5	360	36.0	
New parameterizations	1.9°x2.5° F-case CAM4 w/trop_mozart	25	2	360	18.0	600
TOTAL					**549.5**	**18,720**

Production Experiments

a. Hindcast

In support of the IGAC-SPARC (International Global Atmospheric Chemistry-Stratospheric Processes And their Relation to Climate) Initiative AC&C (Atmospheric Chemistry And Climate), we propose to perform hindcast simulations (1980-present) to identify the model's ability to reproduce the observed long-term changes in tropospheric and lower stratospheric composition. To isolate the role of transport, simulations with SST-forcing (AMIP-type) and using the specified-dynamics option (driven by the NASA Global Modeling and Assimilation Office MERRA data) will be performed using identical emissions and chemical boundary conditions. It will be a complement to a similar project with WACCM (see Whole Atmosphere Working Group proposal) and will help further our understanding of the role of upper stratosphere (and above) chemistry and dynamics.

- SST Forcing only (1970-2009): 40-yr Simulation 1.9°x2.5° F-case CAM4 w/ trop_mozart@360 GAU/yr
- MERRAData (1980-2009): 30-yr Simulation 1.9°x2.5° F-case CAM4_SD w/ trop_mozart@750 GAU/yr

b. AEROCOM

The proposed CAM5 Simulations for AEROCOM will help quantify uncertainties in modeling aerosol processes with the goal to reduce the uncertainties in aerosol radiative forcing on climate. The Simulations will be submitted to AEROCOM intercomparison project and documented for peer-reviewed journal articles. These Results will be useful for the IPCC AR5 report. All simulations are 1.9°x2.5° F-case CAM5@382 GAU/yr

- Aerosol microphysics: aerosol nucleation and impacts on aerosol size distribution, present-day and preindustrial emissions: 2x10-yr
- Organic aerosol: sensitivity to primary OC versus secondary OC: 2x10-yr
- Aerosol Direct forcing diagnostics: total forcing and forcing from individual aerosol component: 6x10-yr

c. Nitrogen deposition

Simulations will be performed to investigate the change in air quality and nitrogen deposition in the United States as a result of climate change and emission changes (anthropogenic and biogenic) following the AR5 scenarios. Focus will be on contrasting present-day and 2050.

- Present-day And 2050 Conditions (RCP8.5 And RCP2.6): 3x10-yr Simulation 1.9°x2.5° F-case CAM4 w/ trop_mozart@360 GAU/yr

d. Chemistry/climate in the 20th Century

In support of the CMIP5 CCSM4 simulations, we performed 1850-2005 simulations to predict (prognostic CAM4 run) the distribution of radiatively-active gases and aerosols, in addition to deposition fields (nitrogen, dust and black carbon). The purpose here is to perform additional simulations to identify the specific roles of climate change and emission (or surface concentration) changes. This is similar in spirit to the single-forcing experiments, and will provide input to AR5 On the driving forces associated with the observed pre-industrial to present-day changes in atmospheric composition. All simulation with 1.9°x2.5° F-case CAM4 w/reduced chemistry@360GAU/yr

- 1850-2005 Control
- 1850-2005 with methane fixed at 1850 levels
- 1850-2005 with ozone precursors emissions fixed at 1850 levels
- 1850-2005 with aerosol emissions fixed at 1850 levels
- 1850-2005 with SSTs and CO_2 Fixed at 1850 levels

e. GeoMIP

Geo-engineering experiments (solar reduction and emissions of sulfate in the lower stratosphere) are being planned under the GeoMIP (Geoengineering Model Intercomparison Project) umbrella, organized by A. Robock (Rutgers). We propose to perform the solar reduction experiments (under the 4xCO_2 and 1%-CO_2 experimental designs) with CCSM4 to be fully comparable to the standard CCSM4 simulations performed as CMIP5 Simulations under the Climate Change Working Group allocation. In particular, these simulations will be performed using the BGC version to identify potential CO_2 feedbacks. The sulfate experiments will be performed with interactive chemistry in CESM using the bulk aerosol model representation. This will be complementary to Phil Rasch's simulations with CAM5 physics.

SO_2 injection experiments: all simulation with 1.9°x2.5° B-case CAM4 w/ trop_mozart@750 GAU/yr

- Control (RCP4.5, 3-member ensemble) 1985-2070
- Test to define amount of SO2 Necessary to reduce warming in 2020: 3x10-Yr simulations
- 2020-2070 RCP4.5 With sulfur injection (3-member ensemble)

f. Decadal prediction experiments

In support of CMIP5, we will perform a decadal prediction experiment (1990-2030) with tropospheric chemistry to study the projected air quality (at the regional scale) under climate and emission changes. This will be done using the same configuration as all the other ensemble members (CCSM4, 1-degree); it will be done in collaboration with the Atmosphere Model Working Group and the Climate Change Working Group.

- 1990-2030 (RCP4.5) Simulation with 0.9°x1.25° B-case CAM4 w/trop_mozart@3000 GAU/yr

g. NRCM-chem

We propose to perform dynamical downscaling of CAM-chem (driven by prescribed SSTs) generated tropospheric chemistry simulations. The downscaling (for present-day and 2050 conditions, RCP8.5) will be done over the Northeast U.S., focusing on summertime conditions (when high-ozone conditions at the surface are found) and performed using the NRCM-chem at the resolution of 6km X 6km. These simulations will enable the study of air quality at the sub-regional level.

- Present-day conditions: 10-yr Simulation 1.9°x2.5° F-case CAM4 w/ trop_mozart@360 GAU/yr
- Future conditions(RCP2.6 And RCP8.5, 2050): 2x10-yr Simulation 1.9°x2.5° F-case CAM4 w/ trop_mozart@360 GAU/yr
- WRF-chem downscaling for summer (3 Months for each of the last 5 Years of the previous simulations): 3x5x3 WRF-Chem. 6x6 Km resolution, 1200 GAU/month

Experiment	**Model Config**	**# of runs**	**# of years**	**GAU / year**	**Total KGAU**	**Total Data Volume (Gb)**
Hindcast	1.9°x2.5° F-case CAM4 w/trop_mozart	1	40	360	14.4	1,980
	1.9°x2.5° F-case CAM4_SD w/trop_mozart	1	30	750	22.5	
AEROCOM	1.9°x2.5° F-case CAM5	2	10	382	76.4	1,500
		2	10	382	76.4	
		6	10	382	229.2	
Nitrogen deposition	1.9°x2.5° F-case CAM4 w/trop_mozart	3	10	360	10.8	360
Chemistry/climate in the 20th century	1.9°x2.5° F-case CAM4 w/reduced chemistry	5	155	360	27.9	5,500
GeoMIP	1.9°x2.5° B-case CAM4 w/trop_mozart	3	86	750	193.5	5,200
		3	10	750	22.5	
		3	51	750	114.75	
Decadal prediction	0.9°x1.25° B-case CAM4 w/trop_mozart	1	41	3,000	123.0	1,920
NRCM-chem	1.9°x2.5° F-case CAM4 w/trop_mozart	1	10	360	3.6	1,100
	1.9°x2.5° F-case CAM4 w/trop_mozart	2	10	360	7.2	
	WRF-chem(6kmx6km)	15	.25	14,400	54.0	
TOTAL					**883.45**	**17,560**

Climate Change Working Group

1. Research Plan and Broad Overview of Objectives

The goal of the Climate Change Working Group is to run and analyze CCSM/CESM simulations of 20th and 21st century climate, and extensions beyond 2100, to understand and quantify contributions of internally generated variability and externally forced climate change to patterns of climate change we have already observed, and those we could experience in the future. This usually involves simplified forcing experiments, long pre-industrial control runs, 20th century simulations with various combinations of natural and anthropogenic forcings, and future climate simulations using different emission scenarios. Single forcing runs, isolating on the contributions to climate change of individual natural (e.g. solar and volcano) and anthropogenic (e.g. GHG, ozone, aerosol) forcings, complement the runs with all forcings by contributing to studies of climate change detection/attribution. Analyses typically target changes in mean climate, changes in variability and extremes, and changes across collections of ensemble members with different scenarios. Initialized decadal hindcast/prediction experiments are also run and analyzed to better quantify time-evolving regional climate change over the next few decades.

Key aspects that help define the nature of the climate change simulations from the model are the equilibrium climate sensitivity and the transient climate response (TCR), and contributions of various feedbacks to the response of the model to external forcings. As new model versions become available, the Climate Change Working Group performs analyses of the model simulations in the context of the size and nature of the feedbacks in the climate system, and how they combine to contribute to climate sensitivity and TCR, and thus the magnitude of the simulated climate changes. Additional analyses of multi-century control runs, and simplified forcing experiments (e.g. 1% per year CO_2 increase) provide contextual information with which to help interpret the climate change signals in the model. A new challenge for the Climate Change Working Group is analyzing the emission-driven CESM (BGC) results in the context of the more traditional concentration-driven model simulations. As the CESM increases in complexity, analyses by the Climate Change Working Group encompass more and more interacting components to help understand and quantify the climate system response.

The Climate Change Working Group is a central element in the DOE/NCAR Cooperative Agreement, and also provides an interface with national (e.g. U.S. National Assessment) and international (e.g. IPCC) climate change assessment activities. Additionally, since the Climate Change Working Group does not do model development, but instead performs production runs and analyzes model simulations, it works across nearly all the other CESM Working Groups, and collaborates particularly closely the Biogeochemistry Working Group, the Climate Variability Working Group, the Polar Climate Working Group, and the Paleoclimate Working Group.

Production Objectives

Production runs address various aspects of the forced response of the climate system, and computing resources are requested to address the following overarching production goals:

- Model runs for the Geoengineering Model Intercomparison Project (GeoMIP)
- Model runs to study the impact on the Southern Annular Mode of increasing CO_2
- Complete the full suite of CMIP5 experiments
- In collaboration with the Climate Variability Working Group and the Polar Climate Working Group, contribute runs to a large ensemble with CCSM4

The term geoengineering refers to the deliberate modification of the environment of the planet to counter some of the climate consequences from increasing CO_2 concentrations. One of the strategies that has been suggested for geoengineering is termed “solar radiation management” (SRM). The Geoengineering Model Intercomparison Project (GeoMIP) explores the response of coupled climate system models to a reduction of solar radiation reaching the earth’s surface either by a diminution of solar constant or by the introduction of stratospheric aerosols into the atmosphere. Both are designed to cool the earth to counter some of the warming from increasing GHGs. This strategy has already been explored by a few modeling groups around the world. Some results of this strategy are summarized in a review paper by Rasch et.al. (2009). To date, each study that has explored the response of the climate system to SRM has applied the geoengineering strategy differently. Thus it is very difficult to compare the simulations that have been done so far. The GeoMIP experiments are designed so that a number of models can do the same experiments in a coordinated way and thereby be readily intercompared. The GeoMIP experimental design is described in Kravitz et al (2010).

Poleward shifts in the extratropical storm tracks and Southern Annular Mode (SAM) are projected in almost all climate models under increasing CO_2, however there is a large range across the models in the magnitude of their SAM response (Arblaster et al 2010). To what extent this range is due to processes in the tropics or the extratropics in the models will be examined with perturbation experiments in those regions with the CAM4 forced with observed SSTs. Results will be contrasted with similar experiments being run in Australia using the Australian Community Climate and Earth System Simulator (ACCESS) model.

There are a few remaining CMIP5 experiments to be completed to augment the CESM contribution to the CMIP5 experiments that will be made available to the international research community and will be assessed in the IPCC AR5.

A large ensemble (40+ members) was previously run with the T42 version of CCSM3. The wide use and community interest in these runs is prompting the production of a large ensemble with CCSM4 at 1 degree. The newer model at higher resolution will complement the earlier CCSM3 coarse resolution runs, and will allow, among other things, assessments of predictability, quantification of model uncertainty, and formulation of probabilistic approaches to climate prediction.

Production Experiments

a. Geoengineering Model Intercomparison Project (GeoMIP) experiments

Led by Jean-Francois Lamarque, the Climate Change Working Group proposes to participate in GeoMIP using CCSM4/CAM4 and to compare our simulations with the rest of the models participating in GeoMIP. In particular, Phil Rasch has applied for resources on DOE machines to produce simulations with CESM1/CAM5. It will be particularly interesting to compare our simulations with those being submitted by that group. We know from first intercomparisons of the two models that they have very different climate sensitivities, low cloud feedbacks, and polar amplification responses. These intercomparisons will help us in understanding the differences between these two important climate models, and will also provide information about climate uncertainty from two models with very different behavior. It will be useful in understanding the impact of geoengineering on the planet, but also useful in understanding the two climate models, and the Earth system more generally. Additional GeoMIP runs with CESM (BGC) will quantify the ongoing effects on ocean acidification of increasing CO_2 concentrations even if the global temperature is stabilized through reduction of incoming solar radiation.

The GeoMIP intercomparison requires that 4 scenarios be run. These runs are based upon perturbations to existing control runs that will be produced with separate resources for the CMIP5 model intercomparison activity. The intercomparison suggests that three realizations be performed for each scenario. We believe that 5 realizations would provide a more robust estimate of variability, but will request 3 realizations for each of the 4 scenarios. Each scenario requires 70 years of simulations. Thus, 840 years of simulation.

In addition, for comparison, we will need to add two additional ensembles to the existing RCP 4.5 two-degree simulation (96 years each), and a two-degree $4xCO_2$ (30 years).

Experience with the fully coupled version of CAM4 (1.9x2.5 degree, 30 layer atmosphere, with the displaced pole 1 degree ocean/sea-ice grid) on bluefire indicates a cost of 326 GAUs per simulated year. Our total request is for 326 x 1062years = 346,212 GAUs.

b. Impact on the SAM under increasing CO_2

To address to what extent the range in the poleward shift in the extratropical storm tracks and Southern Annular Mode (SAM) is due to processes in the tropics or the extratropics in the model, perturbation experiments will be run with the CAM4 forced with observed SSTs. We propose to run a 10 member ensemble for the period 1950-2009. The estimate is 483 GAUs per simulated year. Thus, 600 years will require 289,800 GAUs.

c. Completion of CMIP5 simulations at NCAR

The Climate Change Working Group proposes to complete NCAR's CMIP5 experiments which remain:

- The fixed SST $1xCO_2$ (150 years)
- The fixed SST $4xCO_2$ (150 years)

d. Contribute members for the large ensemble with CCSM4

As part of the Climate Change Working Group contribution to the new large (initially 30 member) ensemble with CCSM4, we propose to perform 24 ensemble members run from 2005-2034. Additional members are being requested through the Polar Climate Working Group resources. These simulations will be branched from the end of an existing 20th century simulation with small perturbations applied to the initial atmospheric state in order to fill out the ensemble members. We anticipate that numerous scientific questions across multiple working groups will be investigated using these simulations.

Experiment	Model Config	# of runs	# of years	GAU / year	Total KGAU	Total Data Volume (Gb)
GeoMIP Comparison	CCSM4 1x1CN BGC	4	280	,1022	286	21,360
Impact on SAM	CCSM4 AMIP 1x1	10	600	483	290	2,580
Fixed SST 4xCO_2	CCSM4 1x1CN	1	60	335	20	260
Fixed SST 4xCO_2	CCSM4 1x1CN	1	60	335	20	260
CCSM4 Ensemble	CCSM4 1x1CN	24	720	628	452	14,180
TOTAL					**1,068**	**38,640**

References

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Climate Variability Working Group

1. Research Plan and Broad Overview Objectives

The goal of the Climate Variability Working Group is to analyze natural and anthropogenically-induced patterns of climate variability in CESM and its component models as a means of furthering our understanding of the observed climate system. The Climate Variability Working Group also conducts simulations with CESM and its component models that enhance understanding of the mechanisms of natural and anthropogenic climate variability. These simulations are motivated by broad community interest and are widely used by the national and international research communities. The Climate Variability Working Group does not conduct development simulations.

Production Objectives

The overarching goal of the proposed production simulations is to quantify uncertainty and enhance understanding of climate variability on a broad range of time scales, from sub-seasonal to interannual to multi-decadal. The source of uncertainty targeted by these simulations is that associated with processes internal to the climate system. This inherent variability exists on all time scales, and as such affects detection and attribution of climate responses to a range of natural and external forcing factors, for example ENSO and greenhouse gas changes. The Climate Variability Working Group fully supports, and will contribute to the analysis of, a proposed 30-member CCSM4 ensemble of 21st century integrations requested by the Polar Climate and Climate Change Working Groups.

Production Experiments

One of the most important sources of uncertainty in climate change and climate variability is that due to processes internal to the climate system. To properly quantify this aspect of uncertainty, lengthy control simulations and/or large ensemble sizes are needed. To isolate processes internal to the atmosphere or atmosphere-ocean mixed layer system from those internal to the fully coupled ocean-atmosphere system, we propose an experimental approach consisting of (a) the standard AMIP formulation (i.e., globally prescribed SST forcing either from observational estimates or from coupled model output), (b) the so-called “pacemaker” design where SSTs are prescribed in a particular region such as the eastern equatorial Pacific and a slab ocean mixed-layer model is used elsewhere, and (c) simulations with CAM coupled to a global mixed-layer ocean model. These experiments have multiple uses and wide appeal in the climate community.

a. AMIP

The Climate Variability Working Group proposes standard CAM4 AMIP simulations using prescribed SSTs during 1900-present from observations and from the CCSM4.0 climate of the 20th century simulations. We propose 5-member ensembles for each SST source, using CAM4 at nominal 1 resolution, for a total of 1100 years of integration (see AMIP entries in Table 1). Comparison of the two sets of AMIP experiments can be used to estimate the relative contributions of natural and anthropogenic components of atmospheric variability over the 20th century.

b. Pacemaker

Despite the pragmatism of the AMIP approach, there are limitations that have implications in terms of estimating the uncertainty due to internal atmospheric dynamics. Specifically, the prescribed SST approach suffers from an energetic inconsistency at the air-sea interface, namely the SSTs do not respond to the atmospheric fluxes. This leads to problematic estimates of predictability - signal to noise ratios can have too much noise. The solution is to use coupled models, but then separating the uncertainty into SST scenario versus atmospheric internal dynamics becomes more challenging. Here we propose a pacemaker approach where SSTs are prescribed in a limited domain where the SST forcing dominates (e.g., tropical Pacific) and the atmosphere is coupled to a slab mixed layer model outside this limited domain. The Climate Variability Working Group proposes to use the same SSTs in the eastern tropical Pacific (20S-20N) as in the AMIP simulations described above except in this case a slab mixed layer model is used outside this region. These simulations along with the AMIP simulations can be used to assess how air-sea coupling affects the pattern of natural and forced climate variability. We propose 5-member ensembles for each SST source, using CAM4 at nominal 1 resolution, for a total of 1100 years of integration (see Pacemaker entries in Table 1).

c. Global MXL

We propose a 500-year simulation of CAM4 at 0.9x1.25 coupled to a global slab ocean mixed layer model (see Global MXL entry in Table 1). In combination with the existing long control integration of CCSM4, this simulation can be used to quantify the contribution of ocean dynamics to estimates of uncertainty in patterns of climate variability. Although unrealistic by design, this model configuration provides a "null hypothesis" of coupled ocean-atmosphere variability against which to benchmark more complex sources of coupled ocean-atmosphere variability.

Experiment	Model Config	# of runs	# of years	GAU / year	Total KGAU	Total Data Volume (Gb)
AMIP Observed SSTs 1900-present; five member ensemble	CAM4 (1 deg)	5	110	401	221	2,365
AMIP CCSM4 SSTs 1900-present; five member ensemble	CAM4 (1deg)	5	110	401	221	2,365
Pacemaker Observed SSTs 1900-present; five member ensemble	CAM4 (1deg)	5	110	401	221	2,365
Pacemaker CCSM4 SSTs 1900 present; five member ensemble	CAM4 (1deg)	5	110	401	221	2,365
Global MXL	CAM4 (1deg)	1	500	401	201	2,150
Total					**1082**	**11,610**

Land Ice Working Group

1. Research plan and overview of objectives

The Land Ice Working Group is responsible for developing and applying the land-ice component of CESM. This component has two parts: (1) a dynamic ice sheet model, the Glimmer Community Ice Sheet Model (Glimmer-CISM), and (2) a surface-mass-balance (SMB) scheme for land ice in the Community Land Model (CLM). Both components are new and are being actively developed and tested. Our overarching goal is to deliver useful and comprehensive projections of land-ice retreat and sea-level rise on decade-to-century time scales. During 2011-12 we will perform a series of first-of-a-kind CESM simulations with a dynamic ice sheet model. We aim to complete many of these simulations in time for inclusion in IPCC AR5.

Development Objectives

The Land Ice Working Group has the following major near-term (1-2 year) development goals:

1. Determine the relative importance of various sources of uncertainty (e.g., poorly constrained boundary conditions and ice physics parameters) in Glimmer-CISM, and quantify the effects of those uncertainties on ice-sheet and sea-level projections. Uncertainty quantification is essential if we are to provide planners and policymakers with useful information.
2. Validate and refine the new surface-mass-balance scheme in CLM. This scheme is already being used to predict Greenland's present-day and future SMB. In the future, it will also be used to force models of the Antarctic ice sheet as well as small glaciers and ice caps as well as ice sheets. A weakness of the current scheme is its very simple parameterization of ice albedo.
3. Implement in CLM a dynamic landunit scheme that allows glaciated regions to become ice-free and vice versa. This will enable century-to-millennial-scale simulations in which changes in ice-sheet extent and volume feedback on the land and atmosphere. We will then be able to simulate the inception and evolution of paleo ice sheets, such as the smaller Greenland ice sheet present during the last (Eemian) interglacial.
4. Implement a scalable, parallel version of Glimmer-CISM with the higher-order dynamics required to simulate the rapid changes being observed in fast-flowing ice. This new dynamical core, or "dycore" will replace the current serial, lower-order dynamical core in a modular fashion.
5. Couple Glimmer-CISM to the POP ocean model (which is being modified to simulate circulation and heat exchange beneath floating ice shelves in Antarctica), and configure CESM for large-scale simulations with an AOGCM fully coupled to a dynamic ice-sheet and ice-shelf model.

Goals (1) and (2) will be supported directly by this proposal. These simulations will enable us to identify model biases, explore sensitivities to uncertain parameters, and test potential physics improvements. The new land-ice component must be validated for preindustrial and present-day conditions and quantify its uncertainties before it can be applied with confidence to climate change scenarios. Goal (3) involves significant coding and software engineering, but only modest computing resources. Goals (4) and (5) are being pursued as part of the DOE ISICLES (Ice Sheet Initiative for Climate at Extreme Scales) and IMPACTS (Investigation of the Magnitudes and Probabilities of Abrupt Climate Transitions) projects, with computing resources provided by DOE. As these DOE-supported development efforts come to fruition, we will seek CSL support for production runs as described below.

Production Objectives

The main goal of near-term production experiments is to simulate the evolution of the Greenland ice sheet under a variety of climate scenarios, including (1) preindustrial and present-day, (2) 21st century, (3) long-term (22nd century and beyond), and (4) previous interglacials. These experiments can be carried out without full ice-ocean coupling. For computationally intensive ice-ocean simulations with a dynamic Antarctic ice sheet, we will seek separate DOE resources.

Several of the experiments proposed here will use new higher-order dycores for coupled climate experiments, following naturally from development goal (4) above. Also, one set of experiments will focus on the Eemian interglacial, following from (3). We expect that before the start of the allocation, many of the experiments described below will already have been done with a shallow-ice dycore. That dycore will be tuned as needed to provide a stable, optimal Greenland simulation for preindustrial and present-day climate, providing a baseline for assessing the importance of higher-order ice-flow dynamics.
High-priority production runs in preparation for IPCC AR5 include (1) coupled preindustrial and 20th century CMIP5 experiments with a dynamic Greenland ice sheet, and (2) coupled century scale CMIP5 climate-change experiments (e.g., RCP 8.5) with a dynamic Greenland ice sheet. CMIP5 runs using the shallow-ice dycore are expected to be complete by April 2011. We will repeat these runs with at least one of the higher-order dycores expected to be available next year. The models will be validated and tuned in an IG configuration (active land and ice-sheet components, data atmosphere, and stub ocean and sea ice) before we carry out production runs in a fully coupled BG configuration.

These century-scale simulations will be complemented by a set of longer-term (~1000 year) simulations to study the stability of the Greenland ice sheet. It has been suggested that with sustained levels of high CO_2, the Greenland ice sheet could retreat irreversibly. Since dynamic time scales are critical for assessing stability, we will use a higher-order ice-sheet dycore. In order to simulate many centuries of climate evolution with available computing resources, we will run the ice sheet model asynchronously (~10 ice-sheet years per AOGCM year).

We also plan to simulate dynamic paleo ice sheets, in collaboration with members of the Paleoclimate Working Group. We will focus initially on the last (Eemian) interglacial, ~125 Ka before the present, when global sea level was several meters higher than today and the Greenland ice sheet was roughly half its current size. We will run the ice-sheet model asynchronously (~10 ice-sheet years per AOGCM year) to allow multi-century simulations. These experiments will be run first with the shallow-ice dycore, then repeated with a higher-order dycore.

Many of the proposed experiments will be run with a fully coupled model, including dynamic ice sheets (i.e., the BG configuration), at a resolution of 0.9ox1.25o for the atmosphere and 1o for the ocean. Others will use active land and ice-sheet models and a data atmosphere (i.e., theIG configuration) at a resolution of 0.9ox1.25o. With a shallow-ice dycore, whose cost is minimal, we assume a cost of 630 GAU/year for BG simulations and 33 GAU/year for IG simulations. The cost of the more complex higher-order dycore is uncertain, but here we assume a cost of 100 GAU per year. Ice-sheet grid resolution can be adjusted as needed to stay within this target. We assume a data volume of 19.7 GB/year and 1.2 GB/year, respectively, for the BG and IG configurations, not including ice sheets. Data volume for the ice-sheet model is projected to be 0.3 GB/year for the shallow-ice dycore and 3.0 GB/year for the higher-order dycore.

2. Proposed experiments and computational requirements

Development Experiments

a. Quantifying ice-sheet uncertainties

We will apply stochastic inversion to quantify the relative importance of various sources of model uncertainty. In particular, we will identify the combinations of uncertain boundary conditions (e.g., climate forcing history and geothermal fluxes) and ice physics parameters (e.g., basal traction) that allow Glimmer-CISM to best approximate the observed geometry and mass balance of the Greenland ice sheet. Given a few representative samples from this ensemble, we will estimate the impacts of these uncertainties on plausible contributions of the Greenland ice sheet to sea-level rise during the next 100-200 years. We will largely follow the experimental protocol of the multi-model SeaRISE community effort. The initial focus will be on the SMB scheme and the shallow-ice dycore. These techniques will then be extended to the higher-order dycore, using accelerated tuning techniques developed by Land Ice Working Group members.

b. Testing a new albedo parameterization for ice sheets

The surface mass balance of glaciers and ice sheets is sensitive to the albedo, which can vary significantly as a function of local conditions. In CLM the snow albedo is computed using the sophisticated SNICAR scheme, but the bare ice albedo is parameterized simply as a pair of numbers (broadband albedo in the visible and near IR bands, respectively). We will improve the treatment of bare-ice albedo by implementing the physically-based broadband albedo parameterization of Gardner and Sharp (2010). We will then analyze the resulting changes in the surface mass balance of the Greenland ice sheet. Much of the validation and analysis can be done in the inexpensive IG configuration, but we would like to repeat the fully coupled 20th century run and one climate-change scenario (RCP 8.5).

Experiment	Model Config	# of runs	# of years	GAU / year	Total KGAU	Total Data Volume (Gb)
Quantifying uncertainties	IG (shallow-ice) IG (higher-order ice)		1500 ~1200 (or more at lower ice-sheet resolution)	33 133 (or fewer at lower resolution)	50 60	2,250 5,040
New albedo parameterization	IG (validation) BG (shallow-ice, 20th century) BG (shallow-ice, RCP 8.5)	1 1	~1250 150 100	33 630 630	43 94 63	1,880 3,000 2,000
TOTAL					**410**	**14,170**

Production Experiments

a. CMIP5 simulations with a higher-order ice-sheet model

Both the steady state of the Greenland ice sheet and its rate of response to climate change are likely to change significantly when the shallow-ice dycore is replaced with a higher-order dycore that can simulate fast flow in outlet glaciers. We will carry out the first fully coupled simulations with a higher-order ice sheet model fully coupled to an Earth-system model. We will perform three standard CMIP5 simulations (preindustrial, 20th century, and RCP 8.5) and compare the results to earlier simulations using the shallow-ice dycore. We expect to publish results in time for inclusion in IPCC AR5.

b. Evaluating the long-term stability of the Greenland ice sheet

Warming expected during this century may be sufficient to induce a negative surface mass balance for the Greenland ice sheet. If this warming is sustained for many centuries, the ice sheet could retreat inexorably, with mass lose accelerated by ice-albedo and height-elevation feedbacks along with dynamic responses (e.g., faster basal sliding triggered by increased meltwater penetration). To explore possible tipping points for Greenland, we will carry out a multi-century simulation (~1000 ice-sheet years with asynchronous coupling) with elevated greenhouse forcing (RCP8.5 through 2300, then CO_2 held constant) followed by several CO_2 stabilization experiments. We will evaluate changes in ocean circulation as well as sea level.

c. Simulating the Greenland ice sheet during the Eemian interglacial

During the height of the Eemian interglacial, global mean sea level was several meters higher than present, and the Greenland ice sheet was about half its present size. The Paleoclimate Working Group has already carried out coupled simulations of the Eemian interglacial with prescribed ice sheet geometry. We will run CESM with Eemian orbital parameters in coupled asynchronous mode, first with the shallow-ice version of Glimmer-CISM and then with the higher-order version. We will determine the time required for the Greenland ice sheet to reach steady state and will compare the simulated ice sheet with geological reconstructions. The resource request assumes that we will use CAM's FV1 dycore, which may provide a more accurate surface mass balance than the FV2 or T31 dycores (which are also supported for icesheet simulations). However, we may be able to perform longer simulations with a less expensive dycore if the simulated SMB is accurate enough. These simulations will be carried out in consultation with members of the Paleoclimate Working Group.

Experiment	Model Config	# of runs	# of years	GAU / year	Total KGAU	Total Data Volume (Gb)
CMIP5 with higher-order ice-sheet dycore	BG (preindustrial)	1	150	730	110	3,400
	BG (20th century)	1	150	730	110	3,400
	BG (RCP8.5)	1	100	730	73	2,270
Long-term Greenland stability with higher-order ice-sheet dycore	BG (RCP8.5 continuation)	1	100 AOGCM, 900 ice sheet	630 AOGCM, 100 ice	153	4,670
	BG(~3 stabilization scenario)	3	100 AOGCM, 900 ice sheet	630 AOGCM, 100 ice	153	4,670
Eemian Greenland	BG (shallow-ice)	1	100AOGCM, 1000 ice sheet	630 AOGCM, Negligible for ice	63	2,270
	BG (higher-order ice)	1	100 AOGCM, 800 ice sheet	630 AOGCM, 100 ice	143	4,370
TOTAL					**805**	**25,050**

Land Model Working Group

1. Research Plan and Broad Overview of Objectives

Over the next several years, the goal of the Land Model Working Group is to continue to advance the state of the art in modeling Earth's land surface, its ecosystems, watersheds, and socioeconomic drivers of global environmental change, and to provide a comprehensive understanding of the interactions among physical, chemical, biological, and socioeconomic processes by which people and ecosystems affect, adapt to, and mitigate global environmental change. Land biogeophysical and biogeochemical processes are intimately linked and therefore it is not easy to separate land biogeophysics development from land biogeochemistry development. For this allocation request the land biogeochemistry model development (which formerly came under the purview of the Biogeochemistry Working Group) has been included in the Land Model Working Group request while the Land Model Working Group production work related to biogeochemistry has been included in the Biogeochemistry Working Group request. Consequently, the majority of the Land Model Working Group allocation request is for support of development activities.

Development Objectives

The Community Land Model version 4 is increasingly suited for investigations of the role of land processes in weather, climate, and climate change including topics such as carbon and nutrient cycling, land cover and land use change, urbanization, and geoengineering as well as the study of feedbacks between the terrestrial and the broader earth system. The Land Model Working Group continues to pursue an ambitious program of model development. To provide the user community with access to the latest developments, one of the aims of the working group is to produce and release a new version of CLM roughly every one to two years.

Since the CCSM4 and CESM1 releases, CLM4 has undergone detailed scrutiny by the broad community of model users and developers. This scrutiny has already revealed, and will continue to reveal, several areas in which the model can be improved. Several biases related to both model biogeochemistry and biogeophysics have been identified. Biogeochemical biases including a high gross primary productivity (GPP) bias in the tropics, generally excessive maximum leaf area indices, and errors in the timing and phase of vegetation phenology. Vegetation carbon content is too high in the tropics and too low over much of the mid- and high-latitudes. Soil carbon stocks appear to be somewhat low everywhere and are very low across the northern high-latitudes. Biogeophysical biases include unrealistically dry Arctic soils which leads to excessively cold soil temperatures and to poorly growing vegetation, especially in permafrost zones and low snow-season surface albedos over the boreal forests. Soil moisture variability remains low near the surface and lake temperature profiles and surface energy budgets are unrealistic. Several of the biases that have been identified appear to be related to interactions between model biogeophysical and biogeochemical processes. One of the aims of the Land Model Working Group and the Biogeochemistry Working Group is to better integrate the biogeophysical model development with the biogeochemical model development, including through the development of a land model testbed in which the biogeophysical and biogeochemical performance of the model can be evaluated in a systematic and coordinated fashion.

The other major model development activity involves expanding the capabilities of the model. Efforts are underway to incorporate additional as yet unrepresented aspects of the land system including methane emissions, prognostic wetland distribution, ecosystem demography, and 3-d canopy radiation. There is also a need to modify the CLM structure to permit transitions at the landunit level (current landunits are vegetated, urban, crops, glaciers, wetlands, and lakes) so that the model has the technical capacity to represent changes in landunit fractions throughout an integration. With 'dynamic' landunits, transitions such as glacier to vegetated or vice versa, vegetated to crops, or vegetated to urban can be represented. This capability is particularly important for the Land Ice Working Group which aims to seamlessly model transient glacial inception and/or disappearance.

Production Objectives

The main objective of the Land Model Working Group is to use CESM to improve the understanding land surface processes and their feedbacks to the rest of the earth's climate system. Model developments for CLM4 and model developments planned for the next version of CLM continue to expand the range of questions that can be addressed with the model. Consequently, the production experiments that are planned for this CSL allocation period focus primarily on the utilization of the new aspects of the CLM modeling system. Vulnerability of North American urban areas to heat waves under a warmer future climate will be assessed through a set of high resolution urban experiments. The new irrigation and crop schemes and the new ecosystem demography scheme will be utilized to expand and enrich the analysis of the impact of the anthropogenic alteration of land cover and land use on climate. Finally, a small portion of the allocation will be used to continue investigations into land-atmosphere interactions. Land-atmosphere coupling, or the degree to which soil moisture anomalies can affect surface air temperature or precipitation, exhibits a wide range of strength across several global land atmosphere models and across several version of CAM/CLM. Land-atmosphere coupling strength and its impact on the simulation in particular of floods and droughts will be studied in CAM4/CLM4 and CAM5/CLM4.

2. Proposed Experiments and Computational Requirements

Development Experiments

In several cases, improved parameterizations that will resolve the biases listed above have already been identified and their incorporation will require only modest amounts of computer time to implement and test the new parameterizations in the latest code version. In other cases, the best new parameterizations have not yet been identified and consequently, considerably more computer time will be required to test and evaluate several potential new parameterizations.
In the table below, we lump the requested resources for model development into several classes of integrations that would be completed during a typical development cycle. For pure biogeophysical aspects, CLM4SP (SP stands for prescribed Satellite vegetation Phenology) will be run for the 1948-2004 forcing data period. For biogeochemistry model development, to permit a faithful comparison against observations, the model needs to be run from pre-industrial time up to present day (~150 years) with transient land cover and nitrogen deposition (this is required because the carbon state of the model is significantly different in a transient relative to an equilibrium simulation). Over the last year, we have gained experience with the CLM4CN spinup process. When model changes are small, then initial conditions from a prior simulation can be used, but for significant changes, a new ~2000 year long spinup is required to bring the carbon and nitrogen states into equilibrium. We have requested time for five CLM4CN spinup simulations. Finally, we include a request for time to do several century-scale CAM5/CLM4CN simulations to test and evaluate the impact of the new parameterizations on land atmosphere interactions. Specifically, model development activities the we anticipate will be completed within the April 2011 to June 2012 CSL period, can be broken down into the following topics:

a. Above ground carbon

Biases in gross primary production, maximum leaf area indices, carbon allocation, and vegetation phenology are all interrelated. Significant work is already complete that improves the photosynthesis model parameterizations in CLM4SP. This work will be extended into CLM4CN and assessed for its impact on the vegetation simulations.

b. Below ground carbon

Soil carbon stocks are low in CLM4CN, possibly due to soil carbon pool turnover timescales that are too rapid. The excessively high turnover timescales may be related to the lack of a representation of anoxic decomposition processes and to the impact of vertical variations in soil climate on soil carbon decomposition rates that are not adequately accounted for.

c. Ecosystem Demography

This Ecosystem Demography approach to vegetation dynamics is a 'statistical approximation' of an individual-based forest simulation model, whereby the population of trees in an ecosystem is grouped into 'cohorts' according to their height, plant type, and disturbance history. The recruitment, growth and mortality of representative trees is tracked through time as is their competition for light, water and nutrient resources. This allows the processes determining vegetation composition and change to be simulated at the stand-scale.

d. Methane emissions

A methane emissions model that includes process-based representations of CH4 production, oxidation, aerenchyma transport, ebullition, aqueous and gaseous diffusion, and fractional inundation has been developed at LBNL and needs to be incorporated into CLM4.

e. Cold region hydrology and prognostic wetland distribution
Several errors and limitations have been identified with cold region hydrology. Revised parameterizations have been developed that maintain a more realistic near-saturated soil column above permafrost (thereby permitting better tundra vegetation growth) and more accurately treats the surface energy balance for partially snow-covered grid cells. A surface water store is being introduced to permit a prognostic wetland distribution. This prognostic wetland distribution is required for, among other things, the methane emissions model.

f. Lake thermodynamics

A revised lake model has been developed that fixes problems with surface energy budget and mixing, reduces errors in partitioning fluxes, includes a more sophisticated snow scheme and soil layers beneath the lake, and incorporates better phase change physics.

g. 3-d canopy radiation

Absorption of solar radiation by canopies is commonly been calculated using a plane parallel model. A model consisting of spherical elements is as readily used and provides several advantages including the capacity to more accurately represent shading of the ground surface at high zenith angles.

h. Fire

A revised fire algorithm that accounts for deforestation fires and explicitly considers human caused ignition and fire suppression as a function of population density will be incorporated.

i. Dynamic landunits

The CLM structure is being modified to permit transitions at the landunit so that the model has the technical capacity to represent changes in landunit fractions throughout an integration. With ‘dynamic’ landunits, transitions such as glacier to vegetated or vice versa, vegetated to crops, or vegetated to urban can be represented. This capability is particularly important for the Land Ice Working Group which aims to seamlessly model transient glacial inception and/or disappearance.

Experiment	Model Config	# of runs	# of years	GAU / year	Total KGAU	Total Data Volume (Gb)
CLM4SP Development	0.9x1.25 CLM4SP	25	60	25	37.5	900
CLM4CN Development	0.9x1.25 CLM4CN	25	150	31	116	4,500
CLM4CN Spinup	0.9x1.25 CLM4CN	5	2000	31	310	12,000
CAM5/CLM4CN	1.9x2.5 CAM5/CLM4N	5	150	382	286.5	2,550
TOTAL					**750**	**19,950**

Production Experiments

a. Urban

A series of CLM4SP offline high resolution simulations over the U.S. will be conducted in support of the SIMMER (System for Integrated Modeling of Metropolitan Extreme Heat Risk) project and to support further science development, understanding, and validation for community users of the urban model. The goal of the SIMMER program is to advance methodology for assessing current and future urban vulnerability from heat waves through integration of physical and social science models, research results, and NASA data. The SIMMER will involve downscaling to regional and local levels, to produce new knowledge about changes in extreme heat events across the United States and parts of Canada as a result of changing climate, land use and the interactions among them. Sensitivity experiments will explore the effects of static versus spatially explicit urban areas, and the effects of space heating, air conditioning, and wasteheat. A set of simulations will be performed with atmospheric forcing determined from downscaled present-day WRF/Noah simulations forced with AR5 20th century CCSM4 simulations. Another set of simulations will be performed with atmospheric forcing determined from downscaled 2046-2065 WRF/Noah simulations forced with AR5 RCP8.5 and RCP2.6 CCSM4 simulations. This set of simulations will include sensitivity experiments designed to assess the potential of various strategies for mitigating urban heat island effects.

b. Irrigation

CLM4 now includes the capability to run with a dynamic irrigation scheme. The simulated irrigation will be assessed in offline simulations and the impact of irrigation on climate will be assessed through several long simulations coupled to CAM including 50-yr simulations with potential vegetation, year 2000 land use/land cover to isolation the effects of land use, and year 2000 land use/land cover plus irrigation.

c. Integration of nitrogen and anthropogenic disturbance models

We intend to utilize the capacity of CLM-ED (Ecosystem Dynamics) to simulate recovery after disturbance to investigate the interaction of land use change, nitrogen availability and CO_2 fertilization. We will a) integrate ED-CLM with the existing CLM model, b) implement the Hurtt et al (2010) land use history database within the ED-CLM framework and c) investigate how the reduction in Nitrogen limitation in recently disturbed ecosystems alters their capacity to capitalize on increased atmospheric CO_2. This will require global simulations with time varying CO_2, temperature and nitrogen deposition fields.

d. Global land atmosphere coupling experiments

Land atmosphere coupling strength, or the influence of soil moisture on temperature or precipitation, will be quantified for CAM4/CLM4 and CAM5/CLM4. The GLACE protocol which involves three 16-member ensembles with free and prescribed soil moisture (whole column and root zone) will be completed for both model configurations. These simulations will complement a series of similar experiments with previous CAM and CLM model versions.

Experiment	Model Config	# of runs	# of years	GAU / year	Total KGAU	Total Data Volume (Gb)
High resolution urban	1/8 degree over US CLM4SP	28	30	180	151	52,920
Irrigation	0.9x1.25 CAM5/CLM4SP	3	50	1,536	230	1,860
Nitrogen deposition vs land use disturbance	0.9x1.25 CLM4CN-ED	5	150	31	23	1,500
GLACE	0.9x1.25 CAM4/CLM4SP CAM5/CLM4SP	 48 48	 0.25 0.25	 401 1,536	 5 18	 44 149
TOTAL					**427**	**56,473**

Ocean Model Working Group

1. Research Plan and Broad Science Objectives

The primary goals of the Ocean Model Working Group are to 1) advance the state-of-the-art in the capability and fidelity of the CESM ocean component in support of specific science objectives of the broad CESM effort, and 2) conduct curiosity driven research with CESM to advance our understanding of the role of the oceans in the Earth system. The latter goal ensures that our working group, through CESM, fully contributes to advancing Earth system science, while the former is absolutely necessary to keep the CESM at the leading edge of ocean climate models. This, of course, requires a continuous high level of effort and support.

Development Objectives

Our overall objective continues to be the world leaders in new model developments and to deliver an improved ocean model to the CESM Community for the next generation of the CESM simulations. We are requesting computational resources to address the following development goals:

- Improving physical and numerical representation of processes particularly related to surface freshwater fluxes and model time stepping,
- Investigating the impacts of bottom topography details on ocean ventilation,
- Adding new subgrid scale parameterization for an anisotropic representation of mesoscale eddy effects,
- Improving the efficiency of our data assimilation framework used to obtain ocean initial conditions for decadal prediction experiments.

The Ocean Model Working Group has established a path forward to adopt the Model For Prediction Across Scales (MPAS) ocean model for use in the next plus one version of the CESM. It is anticipated that this effort will require more than five years to reach maturity. Therefore, in the interim, we are committed to improve and maintain our current model (Parallel Ocean Program, POP) In order to continue to provide a state-of-the-art capability to CESM. Towards this goal, we must focus on addressing some long-standing algorithmic shortcomings of POP. These include: elimination of virtual salt fluxes in favor of true freshwater surface fluxes; elimination of the linearity assumption in the barotropic equation solver procedure to allow fine, i.e., order 1 m, near- surface resolution; and changing the model time stepping algorithm to eliminate the Leap-Frog Scheme to facilitate high frequency coupling, i.e., order 1 h, all desirable for many science applications. Given intense recent interest in sea level rise and incorporation of a land-ice component in the CESM framework, abandoning of the virtual salt flux approach to represent the exchange of freshwater between the ocean and other model components is an urgent model development for POP. Beyond some preliminary exploration of paths forward, we have not engaged in any of these developments in a meaningful way yet. We believe that it is now time to fully engage in these activities, with the caveat that these efforts will require additional human resources as well.

In addition, we will continue to investigate the causes of ocean model biases and to develop new subgrid scale parameterizations. The latter will be mostly through our collaborations with the university community as part of Climate Process Teams (CPTs). For all these development efforts, the broad science objective is to understand the behavior of various model developments, both individually and as they interact with the others. These Interactions are often surprising and must be investigated before a new model is adopted. In addition, we will collaborate with the Biogeochemistry Working Group members to assess the impacts of these new developments on the ocean biogeochemistry, e.g., oxygen minimum zones.

Production Objectives

We are requesting computational resources to address the following production goals:

- Evaluation of new parameterizations and assessing their climate impacts
- Pursuing nested high resolution modeling
- Contributing to the international ocean model intercomparison efforts

The Ocean Model Working Group is participating in two CPTs, One on internal wave driven ocean mixing and another on ocean mixing processes associated with high spatial heterogeneity in sea-ice. An important objective of these CPTs is to document the climate impacts of any resulting parameterizations. In addition, we would like to apply one expected parameterization to a particular science investigation: Arctic halocline destruction through near-inertial wave mixing. In addition, we wish to take advantage of the current work on nested high resolution Regional Ocean Modeling System (ROMS) in CESM, both to study model biases and for downscaling climate information including applications in marine ecosystem response to climate change. A continued community service activity of the Ocean Model Working Group has been to support and maintain the Coordinated Ocean-ice Reference Experiments (COREs) atmospheric forcing data sets. We wish to continue these efforts and perform both ocean-only and ocean-sea-ice CORE Forced hindcast experiments. We will participate in related model intercomparison projects, and freely provide our solutions to the broader user community through the Earth System Grid.

2. Proposed Development and Computational Requirements

Unless otherwise stated, all simulations use the nominal 1^o horizontal resolution versions of all component models. We note that Ocean Model Working Group members are engaged in studies that use eddy- permitting resolutions globally. Because the CESM Computational resources are limited, we do not seek resources for this purpose here—these high resolution studies are performed elsewhere.

Model Experiments

D1. Addressing model shortcomings

Because of some algorithmic and numerical issues, introducing true surface freshwater fluxes in POP will require elimination of a linearization assumption in the barotropic solver as well as implementation of the so-called z* vertical coordinate to address the possibility of thin (in comparison to free surface displacements) uppermost layers. There are also nontrivial issues associated with river runoff and ice fluxes with a surface freshwater flux formulation. In addition, we will collaborate and coordinate our related development work with the Land Ice Working Group as they also plan to modify POP for surface exchanges with the land-ice model. All of these algorithmic modifications and the possible time stepping changes can be tested using the nominal 3° horizontal resolution version of POP in either ocean-only or ocean-sea-ice coupled configurations forced with the (CORE, see section P4) normal-year data sets. We expect at least one hundred 5-year ocean-only and ocean-sea-ice coupled simulations each for testing purposes. After verification of the correct implementations, we will conduct about ten 120-year CORE interannually varying forcing experiments using the ocean-sea-ice coupled configuration again in the nominal 3^o resolution version. The modified version of the model will be similarly integrated for 120 years in the nominal 1^o resolution version. We anticipate that we will need about 5 such integrations, including a control case. The final step is to document the impacts in fully coupled simulations, considering two 100-year experiments with one of them as the control case.

D2. Bottom topography and ventilation of the deep Pacific Ocean

The abyssal Pacific Ocean in CESM is poorly ventilated relative to observations and therefore the water there is too old and void of oxygen. This poses numerous problems for the ocean ecosystem model as well as the interpretation of ocean sediment cores. We will explore the hypothesis that poorly represented bottom topography leads to this ventilation problem, primarily by blocking of important deep-water passageways. Because the problem is already evident in the forced ocean-only configuration, this hypothesis can be initially tested without a fully coupled model. Therefore, first we plan to explore the sensitivity of the deep ocean properties to differently smoothed and/or modified bottom topography considering five 100-year ocean-only simulations. We will then conduct 2 extended ocean-only simulations for 500-years each to document the abyssal impacts and changes in ventilation. One of these longer integrations will be for a clean control experiment. All the simulations will be done using the CORE normal-year atmospheric forcing data sets. We note that we plan to employ the model ideal age tracer to assess the changes in ocean ventilation.

D3. Anisotropic Gent and McWilliams (GM) parameterization

Recent studies based on eddy resolving / permitting model simulations suggest an anisotropic form for the Gent and McWilliams isopycnal transport parameterization instead of its commonly used isotropic form. We are currently updating an earlier implementation of an anisotropic GM operator so that it can be used in our current ocean model version. Such a formulation can have significant impacts on model simulations. We anticipate that the new implementation will be already debugged and ready for exploratory sensitivity experiments by early spring 2011. We request resources for about ten 120-year, ocean-sea-ice coupled CORE interannually forced experiments to document sensitivity of model solutions to various prescriptions of the anisotropic diffusivity coefficients. These coefficients will be provided by our colleagues who are analyzing eddy-permitting simulations. We intend to extend 2 of these simulations to year 240. To assess the climate impacts of such an anisotropic GM formulation, we will also conduct two fully coupled simulations for 100 Years each. As usual, one will serve as a control case.

D4. POP-DART data Assimilation

As part of our IPCC contributions, we have been conducting decadal prediction experiments. An important requirement of these simulations is the specification of ocean initial conditions. As an alternative to our earlier efforts using initial conditions extracted from ocean sea-ice coupled hindcast simulations, we have been taking advantage of our in-house data assimilation system to obtain ocean initial states constrained by historical observations for use in decadal prediction simulations. This work has been in collaboration with the Data Assimilation Research Testbed (DART) Group in CISL. To improve the efficiency of the POP-DART system, we would like to revisit some of our initial choices such as a requirement of writing ocean restart files every data assimilation interval (daily at present) that contributes to the apparent slowness of the POP-DART Assimilation system. Here, we request resources to explore other approaches leading to improved efficiency. We expect to perform many short integrations, and based on our previous experience we anticipate to use 100000 GAUs.

Experiment	**Model Config**	**# of runs**	**# of years**	**GAU / year**	**Total KGAU**	**Total Data Volume (Gb)**
D1. Model development	C 3°	100	500	7	3.5	700
	G 3°	100	500	15	7.5	750
	G 3°	10	1200	15	18.0	1.800
	G	5	600	119	71.4	9,360
	B	2	200	628	125.6	3,940
	C	5	500	99	49.5	7,300
D2. Bottom Topography	C	2	1,000	99	99.0	14,600
	G	10	1,200	119	142.8	18,720
	G	2	240	119	28.5	3,744
D3. Anisotropic GM	B	2	200	628	125.6	3,940
D4. POP-DART					100.0	
TOTAL					**771.46**	**64,854**

Production Simulations

P1. Climate Process Teams (CPTs) participation

In current climate models with coupled multi-category sea ice and ocean components, the heat and tracer fluxes between the ice and ocean are calculated based on the average of all ice categories and a single instance of the upper ocean state. Use of a single column ice-ocean model showed that resolving the high spatial variability in ice-ocean brine exchange has important implications for ocean mixing and consequent sea ice mass budgets that influence critical climate feedbacks. Currently, this method has not been tested or implemented in any climate models and further studies on the Multi-Column Ocean Grid (MCOG) and related processes are necessary. Questions to be explored include: How does MCOG work during the ice growth period? How can MCOG be implemented in 3-D Climate models? How does MCOG influence physical and biogeochemical tracers that have fluxes between ice and ocean? What is the importance of explicitly representing the high ice/ocean flux spatial heterogeneity in climate processes and feedbacks? In order to address these questions, development work is needed to implement the MCOG in the ocean component of CESM, requiring extensive changes in the model's KPP vertical mixing parameterization. Additional work will implement a single column ice-ocean model capability. This development work will be done using other computational resources. Here, we request resources only for the longer MCOG sensitivity experiments. This work is joint with the Polar Climate Working Group and resources are being requested under both working groups. The sensitivity experiments are one 200-year simulation with CORE normal year forced 3° Resolution ocean-sea-ice coupled case, one 240-year simulation with CORE interannually forced 1° resolution ocean-sea-ice coupled case, and one 100-year fully coupled simulation. The corresponding requests for the control cases are included in the Polar Climate Working Group proposal. Because an important aspect of this work is to look at the impacts on the ocean ecosystem, all simulations will be with the ocean ecosystem modules.

P2. Destruction of the Arctic halocline through near inertial wave mixing

The observed diapycnal diffusivity levels under the Arctic Sea Ice are almost at molecular levels. Future climate warming will remove much of the sea-ice and expose the underlying ocean to stronger high-frequency atmospheric forcing, leading to enhanced mixing induced by vertically propagating, resonant, near-inertial waves. It is possible that this mixing will destroy the halocline and bring warm subsurface water to the surface, thereby amplifying the destruction of the sea-ice. The near-inertial wave mixing parameterization is currently being developed by the NCAR members of the CPT on internal wave driven ocean mixing and will be ready to be used by the proposal period. We note that testing of this hypothesis represents a scientific application of this CPT. The ongoing CPT work will lead to a balanced, fully coupled 1850 control simulation. In this proposal, we request resources to integrate one 1850-2100 simulation, using one of the scenarios beyond 2005.

P3. Regional Ocean Modeling System (ROMS) in CESM

P3a. Regional Modeling study of a western boundary current

The aim of this study is to apply nested high resolution ocean modeling of the northwest Atlantic to explore the impacts of increased resolution on reducing the large biases in sea surface temperature and subsurface properties evident in this region in CCSM4. Moreover, such biases exist in ocean-sea-ice coupled hindcast simulations forced with observed atmospheric data sets. Previous high-resolution ocean models have shown skill in representing the Gulf Stream separation and the subsequent North Atlantic Current path correctly. In recent work, the ROMS has been successfully nested at a resolution of 0.1° within 1° POP and CESM in the eastern boundary current region, and we plan to apply this methodology to the northwest Atlantic. We anticipate that testing of both the POP-ROMS coupling and CESM-ROMS framework will require at least twenty 1-year integrations each. In the next phase, we will conduct three 20-year hindcast simulations for a ROMS-only case, an ocean-sea-ice coupled case, and an embedded ROMS in an ocean-sea-ice coupled case. These hindcast experiments will be forced with the CORE interannual atmospheric data sets for the 1988-2007 period. We will then conduct a fully coupled simulation with the CESM-ROMS configuration. The latter simulation will be done for 100 years in either an 1850 or present-day configuration to get stable statistics on atmospheric response to the ocean changes. This coupled simulation will be compared against an existing equivalent control run of CESM.

P3b. ROMS Simulations for the Coral Triangle Region

We are also developing high resolution nested modeling capabilities for applications in marine ecosystem studies. To investigate coral reef bleaching and recruitment under future climate scenarios in the coral triangle (the region of maximum marine biodiversity in the western equatorial Pacific), the ROMS is being embedded in the CESM. This project involves collaboration with the Nature Conservancy, who will use this information to help guide a consortium of southeast Asian governments in their pledge to protect 30% of their marine environments by the year 2020. Furthermore, the model will be used to study the physics of the Indonesian Throughflow (ITF) region in a climate context. The ITF is characterized by a collection of relatively narrow passages that are not resolved in climate models but are nevertheless important for the inter-ocean exchange between the Pacific and Indian Oceans and a region of significant feedbacks between the atmosphere and ocean. For this study, the ROMS resolution is 5 km within the domain 100°E-150°E, 15°S-20°N. It will be run in hindcast mode forced by the CORE interannual atmospheric data sets for the period of 1948 to 2007 and in forecast mode forced by one of the CESM projections for climate change. Simulated Lagrangian floats will be deployed in the model for the purpose of studying the connectivity of the region and from there, together with surface temperatures, infer the response of coral communities to physical forcings. We have computational resources to cover the model setup and testing experiments. In this proposal, we request resources to perform the 60-year hindcast simulation as well as a 40-year forecast experiment for a total of 100 years.

P4. CORE contributions and interannually varying river runoff

A new version of the CORE interannually varying atmospheric forcing data sets for the 60-year period covering 1948-2007 has been recently finalized. The CORE protocol calls for integration lengths for a minimum of four forcing cycles, i.e., 240 years. We plan to conduct four 240-year ocean-sea-ice coupled experiments to assess the sensitivity of model hindcast simulations to various surface salinity restoring coefficients. These experiments represent our contributions to the international, CORE model intercomparison efforts.

In the present CORE data sets, the river runoff data are climatological monthly means. Interannually varying runoff data just became available within the last couple of months. We would like to test the sensitivity of ocean circulation to the interannually varying runoff fluxes. Here, we propose one coupled ocean-sea-ice simulation for 240 years using the 1948-2007 river runoff flux data provided by Dai and Trenberth. The impacts of the changing runoff flux can be assessed by comparing to an existing control case (from above) which uses monthly climatological runoff fluxes.

Experiment	Model Config	# of runs	# of years	GAU / year	Total KGAU	Total Data Volume (Gb)
P1. CPT-sea-ice and ocean mixing	G 3° ECOSYS	1	200	24	4.8	300
	G ECOSYS	1	240	365	87.6	10,944
	B ECOSYS	1	100	938	93.8	4,635
P2. CPT-Arctic Halocline	B	1	250	628	157.0	4,925
P3a. CPT-Arctic halocline	POP-ROMS testing	20	20	800	16.0	346
	CESM-ROMS testing	20	20	1,250	25.0	448
	ROMS-only	1	20	630	12.6	54
	G	1	20	119	23.8	312
	G POP in ROMS	1	20	800	16.0	366
	B CESM-ROMS	1	100	1,250	125.0	2,240
P3b. ROMS coral triangle	Ocean-only ROMS in POP	1	100	2,000	200.0	3,280
P4. CORE	G	4	240	119	114.2	14,976
	G interannual runoff	1	240	119	28.56	3,744
TOTAL					**882.9**	**46,570**

Paleoclimate Working Group

1. Research Plan and Broad Overview of Objectives

Earth's Climate history offers a valuable spectrum of climate states and variability. Understanding what produces these diverse climates is a fundamental question in climate science. This is especially the case, given that Earth will transition to a much warmer climate state over the coming decades to centuries. Looking back to Earth's past on multiple time scales and time periods offers the opportunity to test the CESM for various forcing conditions and improve confidence in the models application to the changing climate.

The goal of the Paleoclimate Working Group is to provide the community with configurations of the CCSM and CESM suitable for application to a wide range of paleoclimate research problems. This includes the ability to add ice sheet boundary conditions, and employ different paleogeography, topography and bathymetry conditions representative of specific time periods in Earth's history. The working group also develops and explores model parameterizations that may help resolve differences between modeled past climates and a range of paleoclimate proxy data. In particular, the working group continues to develop and extend the implementation of an array of isotopes in the CESM.

The working group also carries out control experiments as a part of national and international intercomparison projects. The output from these simulations is provided to the greater community for paleoclimate research purposes. Output from control simulations are also used to drive models of intermediate complexity that simulate details of ocean geochemistry on millennial time scales.

Development Objectives

The development objectives focus on exploring three topics that will extend the CESM models application to a range of topics relevant to past and present climates. These objectives include exploration of horizontal resolution and its impact on the hydrologic cycle, the role of cloud processes on simulated snowfall for glacial conditions and the use of isotopes in expanding the diagnostic capabilities for deep time climate simulations. All three of these activities will provide deeper insight and expanded capabilities in modeling paleoclimates in the CESM.

We are requesting computing resources to address the following development goals:

- Understand the hydrologic cycle in the hothouse climate of the Paleocene Eocene Thermal Maximum (PETM) using the high resolution CAM4
- Explore the sensitivity of the conditions of glacial inception to cloud parameterizations of low stratiform cloud
- Expand the CCSM4 to include oxygen isotopes in the ocean component of the model and compare simulate isotopes to paleo data for the warm Cretaceous climate

Production Objectives

The production objectives focus on the application of the CESM to fundamental questions in basic paleoclimate science. Given the time scales involved, these simulations often require lengthy integrations to address these questions. The two topics that will be explored involve using the diagnostic capabilities of water isotopes to understand long term shifts in the hydrologic cycle and the ability of the CESM to simulate glacial carbon cycle levels.

We are requesting computing resources to address the following production goals:

- Simulate regional variations in oxygen isotope for the past 21,000 years and compare these simulations to the observed record
- Participate in an international intercomparison project to see if models can simulate the observed level of atmospheric CO_2 during the Last Glacial Maximum

2. Proposed Experiments and Computational Requirements

Development Experiments

a. High resolution paleocene eocene thermal maximum simulation

The PETM climate was known to be an extremely warm time period in Earth’s past. Tropical sea surface temperatures were as high as 40°C in the Pacific and polar region sea surface temperatures were around 25°C. Given these warm sea surface temperatures there is great interest in how the hydrologic cycle responded to this hothouse climate regime. In particular, the potential for increased tropical cyclonic activity with associated enhanced meridional transient eddy transport of moist energy to high latitudes is quite possible. Investigation of these issues requires high-resolution climate simulations. A collaborative project is underway between CESM and MMM to use nesting of the NCAR Weather Research Forecast Model (WRF) to answer questions about the PETM hydrologic cycle. The initial stage of this effort requires high-resolution CAM4 simulations. A nominal 0.5 Degree CAM4 simulation will be run for 30 years using specified sea surface temperatures from an existing low resolution CCSM PETM simulation that agrees well with proxy SST data. The results from this simulation will be compared to an existing lower resolution simulation to explore the role of resolution in model simulated hydrologic processes. The output from the 0.5° simulation will also be used in a nesting procedure with the WRF model to telescope to ~5 kilometer horizontal resolution. The CSL Computational resource will be used for only the CAM4 PETM simulation.

b. CAM5 and a glacial inception scenario

CCSM is now able to reproduce the increased snow cover that results from different orbital forcing 115,000 years ago, in which ocean dynamics plays only a minor role in the amplitude of the snow response and the associated cooling. The cooling is significantly moderated by the response of the low arctic clouds, a process that is not well represented in CAM4. The inception experiment will be redone with CAM5/SOM, which features a better PBL and advanced cloud microphysics. The model simulation will use the 0.9x1.25 degree SOM Version of CAM5. This model comes into equilibrium within 60 years. A second 60 year simulation will test the impact of the climate-aerosol feedback with the fully coupled CAM5/aerosol.

c. Cretaceous simulation with isotopes

Oxygen isotopes of carbonates (both marine and terrestrial) remain the primary quantitative proxy for Cretaceous paleotemperature. However, the interpretation of oxygen isotopes as paleotemperature requires several assumptions about Cretaceous environmental conditions (e.g. ocean water isotopic composition) that are uncertain. The objective of these simulations is to directly compare model-predicted isotopes with Cretaceous isotope data from paleosols and marine fossils, and thereby avoid making assumptions about the relationship between temperature and isotopic fractionation. This work will require the development of isotopes in the ocean component of CCSM4, which will take place over the next 6 To 12 months. Coupled CCSM4 runs with a T31_gx7 version will be used for the simulations. Four Cretaceous experiments have already been integrated for ~1500 yrs. These existing simulations will be extended for an additional 500 years with the isotopic tracers enabled.

Experiment	Model Config	# of runs	# of years	GAU / year	Total KGAU	Total Data Volume (Gb)
PETM HiRES	CAM4 (0.47 x 0.63)	1	40	2,017	80.86	684
CAM5 Inception	CAM5-SOM (0.9 x 1.25)	1	60	1,536	92.16	744
CAM5 Inception	CAM5-SOM-Aerosols (0.9 x 1.25)	1	60	2,793	167.58	744
Cretaceous ISO	CCSM4 (T31_gx3v7)	4	500	48	96	3,800
TOTAL					**436.42**	**5,972**

Production Experiments

a. Trace21-Isotope simulations

High-resolution cave records of $\delta^{18}O$ have shown a global signature of climate variability and abrupt change coherent with high latitude signals. It however remains unclear if these $\delta^{18}O$ signals represent local rainfall or not. T31 resolution CAM4 simulations that include prognostic $\delta^{18}O$ will be carried out using sea surface temperatures generated from the existing transient Trace21ka simulation for 20 time slices to form a quasi-continuous time series of atmospheric $\delta^{18}O$ to compare with the proxy data. Additional sensitivity experiments with regionally specified SSTs will be carried out to better understand the source of the model response. The length of the 20 time slice simulations is 100 years. The 30 regionally specified SST experiments are also of 100 year length.

b. PCMIP LGM diagnostic carbon dioxide simulation

The Paleaeoclimate Modelling Intercomparison Project (PCMIP) is an international activity that will combine carbon cycle and paleoclimate modeling with ice-core and paleoclimate records to quantify the carbon-cycle climate feedbacks. The goal of this MIP, in coordination with the Coupled Carbon Cycle Climate Model Intercomparison Project (C4MIP), is to use knowledge about past variations in climate and CO_2 to provide additional constraints for understanding the magnitude of the carbon-climate feedbacks. Simulations will be used to test the hypotheses that changes in the ocean uptake associated with ocean temperatures and salinities and atmospheric wind stresses are important for explaining the drawdown of atmospheric CO_2 to glacial levels. The "diagnostic" CO_2 will be compared to the ice-core CO_2 and the $^{13}CO_2$ records for constraints on land/ocean partitioning.

The last month of the 1000-year CMIP5 CCSM4 1° CN simulation for LGM will be used to initialize the physics and land CN, and the last month of the 1850 BGC control to initialize the ocean BGC, and then run for 500 years to see whether (and how) atmospheric CO_2 approaches the observed equilibrium value of 185ppm. Changes in dust deposition as well as the sedimentary iron source with lower sea level will also be considered. The simulation will be extended beyond 500 years if additional computing time becomes available.

Experiment	Model Config	# of runs	# of years	GAU / year	Total KGAU	Total Data Volume (Gb)
Trace21-ISO	CCSM4 (T31_gx3v7)	60	100	48	288	11,400
PCMIP LGM	CCSM4-BGC (0.9 x 1.25)	1	500	938	460	23,200
TOTAL					**748**	**36,400**

Polar Climate Working Group

1. Research Plan and Broad Overview of Objectives

The primary goal of the Polar Climate Working Group is to improve our understanding of the role of the polar regions in global climate. Toward this end, we seek to better understand and model important aspects of the coupled polar climate system, including ice/ocean/atmosphere/land interactions, sea ice processes and coupled feedbacks. We also plan to explicitly examine the influence of polar climate processes on the global climate system through sensitivity simulations of the CCSM. With new capabilities in the Community Earth System Model, we are examining the relative controls on changing ocean biogeochemistry. The individual studies and the computer simulations required for these studies are detailed below.

Development Objectives

In order to better understand the role of polar regions in the global climate system, continued improvements are needed in the representation of sea ice processes and ice-ocean coupling within the Community Earth System Model (CESM). Additionally, the new capabilities in CESM need to be assessed in Polar Regions and in particular, development work is needed to understand the controls on marine ecosystem functioning in polar seas. Finally, enhanced capabilities are planned in order to quantify the role of changing Arctic freshwater budgets in a changing climate.

Thus, we are requesting development computing resources to:

- Improve the representation of sea ice processes within CESM1
- Explore the influence of the high sea ice spatial heterogeneity on ice-ocean coupling
- Understand the causes of and controls on key biases in the CESM1 simulations of the Arctic Ocean biogeochemistry
- Implement Arctic Ocean freshwater tracers to assess the distribution and fate of different freshwater inputs

Production Objectives

Production simulations address particular polar climate aspects of the CCSM/CESM simulations and seek to understand and quantify their role in the global system. The requested production experiments address a number of overarching science questions, many of which are related to ongoing community activities. Climate simulations have consistently suggested that the Arctic will experience some of the largest changes on the globe in response to rising greenhouse gas concentrations. These changes include amplified Arctic warming, significant sea ice loss, with the possibility of seasonally ice-free conditions being reached within the Arctic this century, and an intensified hydrological cycle. These changes in turn can feedback and modify global climate. In general, our production studies seek to understand the variability and change in polar regions and the influence that these have on the larger system.

Thus, a number of overarching scientific objectives will be addressed with the production studies proposed here. In particular, these will assess:

- The changing high-latitude ocean freshwater budgets and their role in sea ice and ocean variations
- The relative role of drivers of sea ice variability and change
- Future marine ecosystem behavior in polar seas
- The influence of regional Arctic sea ice loss on atmospheric conditions.
- The seasonal-interannual predictability of the sea ice cover

2. Proposed Experiments and Computational Requirements

Development Experiments

D1. General ice model improvements

We anticipate that during the time of this proposal numerous new sea ice model parameterizations and code enhancements that are proposed by the broader scientific community will be tested. Likely items include enhancements to the representation of snow processes, including snow aging parameterizations, improvements to the current melt pond parameterization, and the incorporation of a time-evolving salinity profile in sea ice that is currently under-development at Los Alamos National Laboratory. This will necessitate numerous ice-ocean simulations in order to implement and test these new developments. Here we request ten 10-year simulations of the 3° ocean-sea ice coupled model for this purpose.

D2. Arctic Ocean freshwater tracers

Development work is requested to implement Arctic Ocean freshwater tracers in order to track the distribution and fate of various freshwater inputs. This work is required in order to perform production simulations to investigate the changing Arctic Ocean freshwater budgets and how they influence the downstream production of deep water in the northern North Atlantic. Initial implementation of the tracers will be performed in ice-ocean coupled simulations of the 3o model and we request 50 years of simulation for this purpose.

D3. Investigating the CESM representation of Arctic biogeochemistry

Initial analysis suggests that there are substantial biases in Arctic Ocean biogeochemical fields within CESM. At present, it is not clear whether these result from poor parameterizations of local processes or if the biogeochemical effects of Pacific and Atlantic inflows are poorly represented. We propose a series of experiments to determine controls on the Arctic Ocean N, P, C, and oxygen budgets. A series of experiments will be performed to determine the sensitivity of budgets to physical and ecological variables. Of particular interest is the effect of terrigenous material on nutrient budgets; these fluxes are not represented in the current release of the model. For this study we request six 25-year experiments of the one-degree ice-ocean coupled model with biogeochemistry.

D4. Climate Process Teams (CPT) participation

We propose simulations to support the climate process team (CPT) on ocean mixing processes associated with high spatial heterogeneity in sea ice. In current climate models with coupled multi-category sea ice models, the heat and tracer flux between the ice and ocean are calculated based on the average of all ice categories and a single ocean column. Use of a single column ice-ocean model showed that resolving the high spatial variability in ice-ocean brine exchange has important implications for ocean mixing and consequent sea ice mass budgets that influence critical climate feedbacks. Currently, this method has not been tested or implemented in any climate models. Resources are requested in order to implement a multi-column ocean grid (MCOG) driven by sub-gridscale ice-ocean fluxes within the ocean component of CESM. This will be used to assess how the high spatial heterogeneity in sea ice influences: ice-ocean physical and biogeochemical fluxes, climate processes and feedbacks, and relevant uncertainties in climate models. Resources are requested to implement the MCOG in the ocean component of CCSM and to diagnose the climate implications of the MCOG framework in fully coupled simulations. This work is joint with the Ocean Model Working Group and resources are being requested under both working groups. Here we request resources for control cases including one 200-year control simulation with CORE normal year forcing of the 3o resolution ocean-sea ice coupled model, one 240-year simulation with CORE interannual forcing of the 1^{o} resolution ocean-sea ice coupled model, and one 100-year fully coupled simulation. The resources for sensitivity experiments to be compared against these controls are being requested under the Ocean Model Working Group. Because an important aspect of this work is to look at the impacts on the ocean ecosystem, all simulations will include the ocean ecosystem modules.

Experiment	Model Config	# of runs	# of years	GAU / year	Total KGAU	Total Data Volume (Gb)
D1. General Ice	G 3°	10	100	15	1.5	150
D2. FW Tracer	G 3°	1	50	15	0.750	75
D3. Arctic BGC	G ECOSYS	6	150	365	56.25	6,840
D4. CPT	G 3° ECOSYS	1	200	24	4.8	740
	G ECOSYS	1	240	365	87.6	10,944
	B ECOSYS	1	100	938	93.8	4,640
TOTAL					**244.7**	**23,389**

Production Experiments

P1. Polar freshwater studies

Studies indicate that the Arctic hydrological cycle will intensify in response to rising greenhouse gases. This includes increased precipitation and runoff, increased sea ice melt, and enhanced freshwater discharge from the Arctic Ocean to lower latitudes. CCSM4 has ocean model grid refinements such that Nares Strait is now open in the model. Existing simulations suggest this has important effects on the Arctic freshwater transport. As outlined below, several studies are proposed to assess different aspects of the changing highlatitude freshwater budgets.

P1a. Freshwater tracer experiments

Freshwater tracers have proved useful in understanding the dynamics of the freshwater (FW) export from the Arctic. As such, we propose to incorporate new tracers in CCSM4 to track the distribution and fate of various Arctic riverine inputs, sea ice melt and growth, precipitation, and Bering Sea inflow. Development work to incorporate these tracers is included under our development request. Using this capability, we will address how much of the freshwater added to the Arctic Ocean through runoff and Pacific inflow is quickly removed through ice formation in shelf regions, and how much actually stays in the ocean. Additionally, the tracers in the ice and ocean model will make it possible to investigate how the ice from different source regions moves differently through the Arctic than the liquid FW from these regions. These tracer-enabled simulations will be used to assess changing Arctic freshwater budgets over the 21st century. A 150-year fully coupled simulation (1950-2100) is requested. Past experience suggests that the additional tracers will increase the model expense by about 10%.

P1b. Sea ice melt influence

Additional studies will be performed to isolate the influence of changing sea ice melt input on the polar ocean freshwater budgets. These runs will apply a fixed annual-cycle of ice-ocean freshwater exchange in a future scenario simulation. The fixed freshwater flux will be obtained from late 20th century conditions of CCSM4. This will allow us to assess the relative roles of ice melt input versus other freshwater changes on the Arctic ocean conditions, northern North Atlantic deep water formation, and meridional overturning circulation. It will also allow investigations of changing Antarctic conditions. A 100-year fully coupled simulation is requested for this study.

P1c. Arctic sea ice sensitivity to changing snow conditions

Snow plays an important role in the physical system by insulating the ice pack during the summer melt season. While this would seem to indicate increased snow would lead to increased ice thickness, the snow also plays a competing role during the winter months, during which the snow insulates the ice and reduces ice growth. Considering the complex role of snow in the Arctic, and the changing precipitation regime predicted in the coming century, understanding the importance of snow on Arctic sea ice should play a role in planning future improvements and refinements to the sea ice model treatment of snow. To investigate changing snow conditions we propose a set of four 25-year fully coupled model experiments that apply changes to the timing and amount of snowfall.

P2. Sensitivities in the Arctic sea ice system and the role of ice-atmosphere coupling

CCSM4 simulations indicate that the Arctic may be seasonally ice-free by the end of this century. The path to this new regime is not a smooth trend, but rather includes abrupt transitions. It is presently not clear whether these transitions represent stochastic fluctuations or bifurcation points in the structural stability of climate states. Furthermore, the direct sensitivity of sea ice to key forcing variables - likely a function of mean climate state - has not been quantified in CCSM4. As a modulator of fluxes between the ocean and atmosphere, modifications in ice distributions cause feedback, altering the state of both these systems. Many previous studies diagnosing sea ice sensitivity to physical variables have been conducted in forced-ocean modeling frameworks. Since sea ice can modify key atmospheric variables, these frameworks may alias important sensitivity dynamics, due to fixed atmospheric conditions. We propose a series of sensitivity experiments designed to (1) determine sea ice sensitivity to various ocean and atmospheric variables, and (2) quantify the role of sea ice in ocean-atmosphere coupling under different mean climate states. These runs will use 100-year long fully coupled and forced-ocean-ice control integrations with fixed greenhouse gases. Three different GHG levels spanning pre-industrial to late 21st century will be applied. For each climate state, we will run a fully coupled configuration and an ocean-sea ice coupled run with fixed atmospheric forcing. Atmospheric forcing will be obtained using atmosphere only integrations, with prescribed sea ice and SST distributions taken from 21st century transient simulations. There will be a total of 3 coupled runs, 3 atmosphere only runs, and 3 ice-ocean runs.

P.3 Projected changes in Arctic Ocean biogeochemistry

Presently, much of the carbon that is fixed in the Arctic Ocean surface settles onto continental shelf sediments. Denitrification operating in Arctic continental shelf sediments constitutes a globally important loss of fixed nitrogen and source of the greenhouse gas nitrous oxide. Denitrification is sensitive to the supply of organic carbon exported from the surface ocean. As the Arctic becomes seasonally ice-free, the mechanisms controlling export production will change, significantly altering the Arctic's role in the global nitrogen cycle. However, while this may constitute a massive perturbation of the Earth system, our current understanding of the mechanisms controlling export production is insufficient to predict even the sign of change. For instance, warmer waters tend to promote tighter trophic coupling; thus more surface respiration, and reduced nutrient supply due to enhanced stratification, resulting in reduced export production. On the other hand, longer growing seasons, greater bloom extents, and enhanced nutrient replenishment from more energetic fall overturning all point toward more export production. Changes in terrigenous nutrient and carbon inputs to the Arctic Ocean may also impact rates of export production, with local to basin-scale effects. Sensitivity experiments are proposed to diagnose the degree to which export production is sensitive to temperature and ecosystem parameterizations. This will include analysis to identify 3-5 key ecosystem model parameters to which export production is sensitive. Ocean-ice simulations at 3^o resolution will be performed with various parameter values. These will be forced with atmospheric conditions that are consistent with low and high GHGs. A total of eight fifty-year simulations of the ocean-sea ice coupled model with the marine ecosystem at 3^o resolution are requested.

P4. Atmospheric response to Arctic sea ice loss

The response of the atmosphere to sea ice changes is complex. It is a product of both the patterns and amount of sea ice loss, which itself depends on the model studied and the greenhouse gas scenarios used to force the model. We propose to break the signal into its components and run sensitivity studies altering prescribed sea ice in different marginal seas to study the individual impact on the atmospheric circulation. This will be accomplished by prescribing sea ice and sea surface temperature to CAM4 with sea ice removed from one region of interest to provide strong forcing to the system. The regions include: N. Canada (Hudson, Baffin, and Labrador Seas), Atlantic (Greenland, Barents and Kara Seas), Eurasian (East Siberian and Laptev Seas), and Pacific (Bering, Chukchi and Beaufort Seas). A final simulation will study the response of the system with the full signal, i.e. sea ice extent as prescribed from the CESM model for the year 2080-2099. For each of these five test cases we request two sets of runs: the first with SST fixed at the freezing point temperature and sea ice changed, and the second where both SST and sea ice are allowed to vary. Each of these 10 simulations will be run for 50 years. We will use CAM4 for these runs for consistency with previous work and existing simulations.

P.5 Sea ice predictability

Simulations with CCSM3 have been used to assess the inherent predictability on seasonal to interannual timescales in Arctic sea ice under a variety of climate states. We propose to build on these studies by investigating factors that contribute to a degradation of this potential predictability in the real system. This will include experiments to assess the influence of initial state biases in ice conditions on the realized predictive skill. Additional experiments will address the role that sparse observations of key variables such as ice thickness play in limiting predictive capability. These simulations will contribute to Arctic observing network design considerations that are currently underway. To create a large-ensemble in order to diagnose the predictive signal above the inherent noise in the system, we request forty 5-year long simulations of the fully coupled model. Twenty of these will apply random anomalies to initial sea ice conditions to mimic observational error. The other twenty simulations will use a sparse distribution of initial conditions (consistent with current observations) and fill in the required initialization data using correlation length scale analysis.

P.6 Contribution to large ensemble set

Computational resources are requested in order to perform some members of a large 30-member ensemble of CCSM4 simulations for the time period 2005-2034. These simulations will be branched from the end of an existing 20th century simulation with small perturbations applied to the initial atmospheric state in order to fill out the ensemble members. We anticipate that numerous scientific questions across multiple working groups will be investigated using these simulations. From the Polar Climate Working Group perspective, we will use these simulations to assess inherent predictability in the sea ice cover and other polar climate variables, investigate the detection and attribution of polar climate change, and assess the changing likelihood of extreme polar climate events. In order to contribute to this ensemble, we request resources for 6 members of 30-years in duration of the fully coupled CCSM4 model. Additional members are being requested through the Climate Change Working Group resources.

Experiment	**Model Config**	**# of runs**	**# of years**	**GAU / year**	**Total KGAU**	**Total Data Volume (Gb)**
P1 Freshwater P1.1 FW Tracer P1.2 Ice Flux P1.3 Snow	B (+ tracers) B B	1 1 4	150 100 100	690 628 628	103.5 62.8 62.8	2,955 1,970 1,970
P2 Ice Sensitivity	F G B	3 3 3	180 300 300	401 119 628	72.18 35.7 188.4	774 4,680 5,910
P3 Arctic BGC	G 3° ECOSYS	8	400	24	9.6	1,480
P4 Atm Response	F	10	500	401	200.5	2,150
P5 Prediction	B	40	200	628	125.6	3,940
P6 Large Ensemble Contribution	B	6	180	628	113.04	3,546
TOTAL					**974.12**	**29,375**

Software Engineering Working Group

1. Research Plan and Broad Overview Objective

The role of the Software Engineering Working Group is to coordinate the computational development of the CESM model components, oversee the evolving design of the CESM as new components and model physics are added and optimize the model system to obtain optimal throughput and efficiency for an increasing number of model configurations and resolutions on a wide variety of platforms. The Software Engineering Working Group is also responsible for overseeing major releases, such as the recent CESM4 and CESM1, to the CESM community. In addition, we also anticipate the frequent releases of updates to CESM1 to account for bug fixes, the inclusion of new scientific support for model configurations (e.g. low resolution paleo-climate) and the inclusion of out-of-the box support for new computational platforms. Consequently, the Software Engineering Working Group is actively involved in all stages of CESM production and development. In terms of the CSL allocation request, this work can be divided into the areas of model testing, performance tuning and debugging.

Numerous tests are carried out for each new CESM revision on all production platforms to ensure required functionality (such as exact restart capability), correct results (such as bit-for-bit reproducibility where it is expected), tracking of memory and performance metrics (to determine if these have changed relative to the previous revision) and other key production requirements (such as optimizing performance of new revisions, especially where new component science has been introduced). The creation of CCSM4 and CESM1 has been associated with ambitious new scientific and software development across all model components and could not have been successfully achieved without the existence of the CESM test suite. In addition, carrying out the long-term simulations associated with the CMIP5 experiment suite has resulted in development revisions being created, sometimes on a weekly basis. Finally, with the release of both CCSM4 and CESM1 to the user community, periodic creation of release updates will now require extensive testing of the release code base.

The Software Engineering Working Group also supports carrying out load balancing simulations before a production run is undertaken in order to ensure optimal throughput and efficiency for the given experimental configuration. Each load balance exercise requires running a series of 20-day simulations of the production configuration with no I/O. Normally, about 5-10 simulations are required to achieve optimal load balance for the run.

Finally, unexpected problems may arise in the process of new science development as well as in carrying out production simulations. The occurrence of these problems often requires extensive debugging that must be carried out in a time critical manner by members of the Software Engineering Working Group.

Development Objectives

Testing

The creation of each CESM revision currently involves the execution of 115 short tests to ensure reliability on CSL production machines. Each test type is often run in more than one resolution and with a variety of component configurations. If a test fails, one or more additional tests are required to validate bug fixes to the original failed test. These tests often find subtle problems, such as use-before-set and out-of bounds references and unexpected performance slow downs that can be remedied before a production run is started. Historically, the CESM test suite has successfully detected many unanticipated problems before major computational and scientific resources have been expended in long production runs.

Current test cases include the verification of performance throughput, the determination of memory high water marks, and functionality tests for exact restart, branch startup and hybrid startup. Each of these tests is often performed for a variety of model configurations and resolutions. With the creation of CESM1 (and the introduction of a new land ice component, CAM5 and the alternative capability of ESMF component interfaces) the test parameter space has rapidly expanded and resulted in a regression validation test suite of increasing complexity.

As CESM science continues to rapidly evolve driven by both internal development and external collaborators such as DOE's SciDAC project, additional tests covering new scientific or software functionality will be added increasing the number of configurations and resolutions that need to be covered by the CESM test suite. It is important to note that a test is only run one time if it executes successfully the first time. If a test fails, however, one or more additional tests are always required to validate bug fixes to the original failures.

Performance Tuning
A CESM load balancing exercise involves the process of determining the optimal number of MPI tasks and OpenMP threads for each model component in a given CESM configuration and resolution and targeted processor count. The determination of efficient load balancing for a given configuration can result in a dramatic reduction in the cost to perform long simulations.

Debugging
Unexpected problems periodically occur during model development, testing and production runs. These can be due to system issues or can arise from exercising the model with new physics, processor layouts and new resolutions. The Software Engineering Working Group utilizes the CSL allocation to track down these problems as they arise. Resolving these issues quickly benefits all working groups and is critical to the success of utilizing the CSL allocations of the other working groups.

2. Proposed Experiments and Computational Requirements

Development Experiments

Testing: Running a single instance of the CESM test suite requires 7 kGAU. We request 35 kGAU/month for CESM testing. This would permit the capability of having 2-3 new development versions and a release update to be created each month.

Performance Tuning: Based on the expected growth in component complexity across the CESM system as well as past needs, we request 3 kGAU/month for load balancing and performance tuning.

Debugging: Based on the expected growth in component complexity across the CESM system as well as past needs, we request 2 kGAU/month for resolving unexpected system issues.

Total for development is 40 kGAU/month.

Production Experiments
Due to the requirements of the Software Engineering Working Group allocation request, there will be no production allocation requested.

Whole Atmosphere Working Group

1. Research Plan and Broad Overview of Objectives

The goal of the Whole Atmosphere Working Group is to facilitate continued development of the Whole Atmosphere Community Climate Model (WACCM) as part of CESM, and to use WACCM to understand the couplings between atmospheric layers, the role of chemical and physical processes in defining these couplings, and the interaction between the Earth's atmosphere and the sun. WACCM simulations will be used to study the effects of a changing stratosphere on tropospheric climate, including the response to increased greenhouse gases, changes in stratospheric ozone and geoengineering. Development activities intend to take advantage of recent improvements in physical processes in CAM5, add new capability to the model, as well as address deficiencies in WACCM highlighted in recent assessment activities.

Development Objectives

It is important that WACCM stay current with the ongoing development of CESM. Therefore, we plan to update WACCM physics to use the same modules as CAM5. This will enable inclusion of the aerosol indirect effect and a better handling of radiative transfer in general, as well as provide other improvements in the representation of the atmosphere. In addition, in preparation for the transition to the NWSC and the prospect of utilizing 1000s of processors for a single simulation, we intend to begin testing WACCM with the HOMME dynamical core on a cubed sphere. This will enable WACCM to run at significantly higher horizontal resolutions than the typical 1.9 X 2.5. Short-term runs at high resolution have the potential to resolve waves now parameterized in WACCM, which will provide constraints on model parameters.

The stratospheric jet in the Southern Hemisphere in austral winter has typically been too strong in WACCM, which leads to a cold bias (up To 10K) throughout much of the stratosphere. This, coupled with a very late breakdown of the stratospheric vortex, leads to an overestimation of temperature trends over Antarctica, complicating the assessment of the role of ozone recovery and climate change in the SH, and their influence on tropospheric climate. Therefore, it is imperative that we improve the SH Winds and temperature climatology in future versions of WACCM. We believe this can best be achieved by improving gravity wave parameterization.

The newly developed inertial gravity wave (IGW) module enables WACCM to generate Quasi-Biennial Oscillation (QBO) internally, but the period of the simulated oscillation is shorter than the observed mean period of ~28 months. We plan to conduct a parametric study of the IGW module and the QBO period. In addition, we will also test the IGW package for application at middle and high latitudes, both idealized and as tied to mountain ranges. This may help solve the cold bias in the Southern Hemisphere polar region.

The Stratospheric Processes and their Role In Climate 2nd Chemistry-Climate Model Validation (SPARC CCMVal-2) activity showed that most CCMs, including WACCM, do not correctly reproduce the activation of chlorine, which leads to errors in predicting polar stratospheric ozone loss. This is most likely a result of the way in which sulfate surface area density (SAD) is specified. We plan to implement a new approach for deriving SAD that we have developed. In addition, a new update to the Jet Propulsion Laboratory "Chemical Kinetics and Photochemical Data For use in Atmospheric Studies" has been released. We will need to update WACCM to the new recommendations and test the implementation.

CCMVal-2 also highlighted the need for an improved representation of volcanic aerosol heating. The current volcanic heating approach in CAM4 tends to overestimate the heating for large volcanic eruptions. The overestimate is related to a mismatch between the derivation of the H2SO4 mass and composition in the chemistry routine and the optics used in the WACCM4 radiative transfer module (CAMRT). We will conduct testing and development of a new volcanic heating approach using the CAM5 RRTMG radiative transfer module.

We propose to evaluate the effects of stratospheric geoengineering with sulfate aerosols. This will require further development of the Community Aerosol and Radiation Model For Atmospheres (CARMA) microphysical package, which has recently been incorporated as an option in CESM, for detailed simulations of the response of stratospheric sulfate to geoengineering, and calculations of impacts on radiation and chemistry. A sulfate model has been developed with a previous version of CARMA attached to WACCM3, and is currently being adapted for use in CESM.

Production Objectives

We request resources to conduct additional CMIP5 simulations to predict of the evolution of ozone and other radiatively active species in the middle and upper atmosphere and their effects on tropospheric climate under a variety of future scenarios, including those incorporating geoengineering.

We also intend to evaluate the simulation of the circulation in the upper troposphere and lower stratosphere (UTLS), a region where the abundance of water vapor and ozone can have an important effect on tropospheric radiative fluxes. We will compute age of air (AOA) statistics and compare these to observations in order to assess the strength and seasonal variability of the model circulation in the UTLS.

Finally, we propose to test the implications for stratospheric composition and climate of new estimates of spectrally-resolved solar irradiance variability obtained by the Solar Irradiance Monitor (SIM). These observations suggest a much different distribution of irradiance as a function of wavelength than predicted by current empirical models of solar variability.

2. Proposed Runs and Computational Requirements

Development Experiments

a. Developing WACCM5

WACCM will be updated with CAM5 physics. The version of WACCM using an interactive ocean will need to be balanced again for pre-industrial conditions, requiring a series of tuning simulations (est. 5 X 10 yr), and an extended baseline integration (100 Yr of simulation). We will then begin testing the HOMME Dynamical core at 1.9 X 2.5 To verify that the climate and constituent climatologies are unchanged with the change in dynamical core (est. 5 X 10 Yr of simulation).

b. Development of new gravity wave parameterization

An improved diagnostic for gravity wave generation from frontal and baroclinic sources will be developed. The ‘frontogenesis’ function currently used neglects GW generation from upper level jets as well as strong wind shear regions in the lower stratosphere. These can contribute significantly to gravity wave generation both in the Northern and Southern extratropics. We will implement the calculation of the residual to the nonlinear balance equation (Zhang, 2000) to produce a better diagnostic of gravity wave generation from frontal systems with the aim of improving the representation of GW generation.

Little effort has been spent in the past to validate the current orographic GW Parameterization in CESM – a key mechanism for gravity wave generation in the extratropical Southern Hemisphere. In collaboration with Dr. Varavut Limpasuvan (Coastal Carolina University), large-area mesoscale model simulations over South America will be used to verify and improve the parameterization of orographic GW Generation over this region.

We will perform simulations with WACCM4 to develop an improved GW Parameterization with the aim of improving the simulation of SH Temperature and ozone. We budget 200 Yr of simulation to develop improved orographic and frontogenesis components.

c. QBO and inertial gravity waves (IGW) parameterization

The most important parameters that will affect the gravity wave forcing and QBO period in the IGW Parameterization are wavenumber, spectral shape of the wave source, anisotropy, and intermittency. We will also test the feasibility of tying the IGW source to deep convection. In our preliminary tests, at least 4 QBO cycles are needed to evaluate its periodicity and its variability, and we are planning to test 10 groups of parameters. This will require approximately 120 Yr of simulation.

d. Improvements in model chemistry

Heterogeneous Chemistry: The new SAD Module will be tested in WACCM nudged with reanalysis data referred to as “specified dynamics” or SD-WACCM. Several tunable parameters will be examined (particle densities, super situation thresholds, settling velocity size distribution widths, etc.) Comparison of the model results to aura MLS observations for specific winter / spring periods will be the ground truth for adjusting these parameters. We will require a total of 20 X 1 Yr simulations using the 125 Species version of SD-WACCM.

Updating WACCM gas-phase chemistry to JPL-2009: A new update to the Jet Propulsion Laboratory “Chemical Kinetics and Photochemical Data For use in Atmospheric Studies” has been released. We will need to update WACCM4 to the new recommendations. This effort will be done in stages using the specified dynamics version of the model. This work will also benefit the Chemistry Climate Working Group. We will need approximately 5 X 1 Yr simulations of SD-WACCM.

e. Improved volcanic heating specification

A new volcanic heating approach will be developed using the RRTMG radiative transfer module following development of WACCM5. Approximately 25 Yr of computation will be required.

Experiment	**Model Config**	**# of runs**	**# of years**	**GAU / year**	**Total (KGAU)**	**Total Data Volume (Gb)**
WACCM5 development	W5/60sp/66l/2x W5/60sp/66l/HOMME	5 1 5	10 100 10	1.8 1.8 1.8	90 180 90	2,750 5,500 2,750
Improved GW parameterization	W4/60sp/66L/2x	20	10	1.4	280	11,000
QBO	W4/60sp/66L/2x	10	12	1.4	168	6,600
Chemistry improvements	W4/125sp/88L/SD/2x	20 5	1 1	2.4 2.4	48 12	4,000 1,000
Volcanic heating	W5/60sp/66l/2x	1	25	1.8	45	1,375
Total					**913**	**34,975**

Production Experiments

a. CMIP5 Simulations

WACCM4 simulations performed as part of CMIP5 included RCP4.5 only in future climate predictions. We will investigate the range of the future climate response by performing simulations using RCP8.5 And RCP3-PD. This will require an ensemble of 3 simulations for each of the two scenarios from 2005-2050 (2x3x46 yr).

b. Geoengineering simulations

Four standard forcing scenarios have been proposed under the Geoengineering Model Intercomparison Project (GeoMIP, Kravitz Et al., Atmos. Sci. Lett., 2010). We will perform the four recommended experiments (G1-G4) to explore the extent to which stratospheric aerosol geoengineering might offset climate change projected in some of the CMIP5 experiments. Experiments G1 and G2, covering the period 2020-2070, involve reducing the solar constant in the model to offset time-invariant and time varying increases in CO_2 from pre-industrial conditions (2x51 yr). Experiments G3 and G4 involve simulation of a sulfate layer to achieve such a dimming effect between the years 2020 and 2070, following differing sulfate scenarios. The CARMA microphysical code will be coupled to WACCM for some of the simulations of the sulfate layer (2x51 yr).

c. Evaluating chemical processes that affect climate

Examining the detailed observational record of the historical period is useful for validating chemical constituents (e.g., ozone) that are projected to change in a future climate. A new NASA-funded Dataset called GOZCARDS (Global Ozone Chemistry and Related Trace gas Data Records for the Stratosphere) will be used to evaluate chemistry/climate processes in WACCM. GOZCARDS includes a detailed integration of multiple satellite instrument data sets. For this work we will run SD-WACCM using dynamical fields from 1979 to 2010; A 10-year model spin up will be required before the time-dependent simulation is started (32 + 10 = 42 yr). The meteorological fields used for this simulation will be from the NASA Modern ERA retrospective-analysis for research and applications (MERRA). This simulation will also be compared to a fully interactive simulation from 1960-2010, which requires a 10-year model spin up (10 + 51 = 61 yr). This activity parallels simulations done by the Climate Change Working Group and will allow the study of the influence of the upper atmosphere on climate changes related to chemical processes.

d. Evaluating VSL halogen impacts on ozone

Short-lived halogen species (i.e., organic and inorganic gases with lifetimes of less than 0.5 years) have recently been shown to be important catalysts of ozone loss and methane oxidation in the marine boundary layer. Tropospheric ozone, the oxidizing capacity of the troposphere, and the lifetime of methane in the atmosphere are affected and therefore this process is important for understanding anthropogenic climate change. In addition, short-lived bromine compounds may contribute substantially to stratospheric ozone loss. Many of the chemical processes in the troposphere will be evaluated using CAM-CHEM (allocations requested by the Chemistry-Climate Working Group). However, for understanding the impact that VSL species have on historical ozone trends, we will use WACCM. For this simulation we will update the 1960-2010 simulation described above, with the addition of the extra VSL species. Resources needed: 10 Yr spin-up + 51 Yr run = 61 Yr using the 150-species, 66-level version of WACCM4).

e. Diagnosing the circulation of the Upper Troposphere-Lower Stratosphere (UTLS)

A growing body of evidence points to the importance of troposphere-stratosphere coupling for climate variability and change, with implications for surface climate, and the need for IPCC type climate models to fully represent this coupling. However, the interplay between radiation, dynamics, and chemistry in the UTLS Is poorly understood in detail and remains a challenge for climate models. We will test the representation of lower stratospheric transport pathways and their associated timescales in current CCMs by studying age-of-air (AOA) spectra and their seasonality in WACCM, And comparing the results with observational estimates such as those of Bönisch Et al. (2009). This requires 15 Yr of simulation to determine the necessary AOA spectra and associated quantities using CESM/WACCM4 with specified SST for the period 1996-2010.

f. Solar Impact on decadal prediction of climate

We will study the impact of the solar cycle on climate variability and its implications for decadal climate prediction. We plan to conduct decadal hindcasts with initialized oceans in parallel to existing CMIP5 “low-top” simulations. We will evaluate the accuracy of the WACCM hindcast compared to the existing simulations, and estimate the influence of solar variability by running with and without a variable solar spectral irradiance. We plan a total of 6 11-year integrations: two ensembles of 3 members each, with and without solar variability (2x3x11 yr). 7. Evaluating the impact of new solar spectral irradiance measurements the predictions from the solar spectral irradiance derived from the Solar Radiation Physical Modeling (SRPM) tools (Fontenla, 2009) are significantly different from the current spectral irradiances used in WACCM CMIP5 simulations. We will run a 25 Yr simulation (~1985 To 2009) With SRPM Spectral irradiances and compare the atmospheric response to existing CMIP-5 Simulations for the same period (which used irradiances from the empirical model of Lean).

Experiment	**Model Config**	**# of runs**	**# of years**	**GAU / year**	**Total (KGAU)**	**Total Data Volume (Gb)**
CMIP5	W4/60sp/66L/2x	6	46	1.4	386	15,180
GeoMIP	W4/60sp/66L/2x W5/CARMA	2 2	51 51	1.4 3.2	143 326	5,610 20,400
Chemical processes	W4/125sp/88L/SD/2x W4/125sp/66L/2x	1 1	42 61	2.4 1.8	101 110	8,400 269
VSL halogen chemistry	W4/150sp/66L/SD/2x	1	61	2.2	134	12,200
Diagnosing UTLS circulation	W4/60sp/66L/2x	1	15	1.4	21	825
Solar variability in decadal prediction	W4/60sp/66L/2x	6	11	1.4	92	3,630
Impact of solar spectral variability	W4/60sp/66L/2x	1	25	1.4	35	1,375
Total					**1,348**	**67,889**

TOTAL request: 913 K + 1348 K = 2261 K GAU Over 15 Months = 151 K GAU / month

* The Request is ~50% over the guidelines. If this cannot be met, then the Whole Atmosphere Working Group considers model development (particularly addressing known biases and staying current with CAM5) a higher priority, and would forgo these simulations for CMIP5 and GeoMIP. Without these simulations the request is 103 K GAU / month.

References

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CCSM gratefully acknowledges our primary sponsors,
The National Science Foundation and
The Department of Energy