CESM

Community Earth System Model

Proposal for CSL Resources

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Period of Performance: 8/1/12 – 1/31/14

Total Request: 175.6M Core Hours

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CSL Proposal Summary

Introduction

The Community Earth System Model (CESM) project is a true community effort including 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. The continued development and application of this modeling system has been largely facilitated through access to Climate Simulation Laboratory (CSL) computational resources. The CESM and its predecessor, the Community Climate System Model (CCSM), have been at the forefront of international efforts to understand and predict the behavior of Earth's climate. CCSM (and more recently, CESM) output has been used in many hundreds of peer-reviewed studies to better understand the processes and mechanisms responsible for climate variability and change. CESM source code and simulation output are made freely available to the broad scientific community. Additionally CCSM/CESM simulations have been important contributions 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). CESM 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.

With development resources under previous CSL allocations, the CCSM transitioned from a purely physical climate model to an earth system model with the ability to simulate biogeochemical cycles, ice sheet properties and active chemistry. These and other new model capabilities have enabled investigations into a wide range of pressing scientific questions providing new predictive capabilities and increasing our collective knowledge about the behavior and interactions of the earth system. This proposal for CSL resources (over the period from August 2012 through January 2014) 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. The exciting opportunities afforded by the transition to the NCAR-Wyoming Supercomputing Center (NWSC), with considerably enhanced computational resources, will allow for the incorporation of new processes and capabilities within CESM and the study of spatial and temporal scales not previously possible.

With the transition to an Earth System Model, community involvement in the CESM development and application has expanded, 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 and 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. This resulted in draft working group plans. In addition, some high profile across-working group projects were identified that fulfill multiple purposes and will be of interest to a broad research community. These are in addition to the working group plans and are described as “community projects” in the appendix. This collection of draft 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 and community projects, 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. During the previous CESM proposal preparation, a similar process was implemented and we believe resulted in a 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 have been and remain critical for the CESM project, and without them the many notable achievements since the last CSL award would not have been possible. The following is only a brief overview of some of the major model developments and achievements under the previous CESM CSL allocations. More detailed summaries (by working group) can be found in the CSL Accomplishments Report.

a. Model Development

Atmosphere (AMWG)
CSL resources have allowed for major advancements for both physical parameterizations and dynamical core developments with the Community Atmosphere Model, 5 (CAM5) model version. The incorporation of new cloud-aerosol-radiation process representations in CAM5 have lead to the most skilled reproduction of the observed 20th century global temperature record of any current version or predecessor of CESM. Additional developments are underway and have made significant progress using CSL resources. The cutting edge UNIfied CONvection Scheme (UNICON), which represents the entirety of unresolved moist asymmetric turbulence from the earth's surface to the tropopause, is now implemented and has the capability of working more continuously across the large range of current and potential future grid resolutions. Inclusion of the Cloud Layers Unified By Binormals (CLUBB) within CAM has proceeded and will potentially allow a more unified framework for boundary layer, shallow convection and large-scale cloud parameterizations. Development work has progressed on the computationally scalable spectral element dynamical core (CAM-SE). This is enabling high resolution simulations which exhibit excellent tropical cyclone statistics. Additionally, the implementation and use of the CFMIP Observational Simulator Package (COSP) has allowed for a robust evaluation of cloud properties in CAM. Progress on a prescribed modal aerosol model version of CAM5 has been significant and will allow for less computationally intensive experiments. Overall, notable CAM advancements have been accomplished with CSL resources, allowing it to remain and in many cases lead state-of-the-art developments.

Atmospheric Chemistry (CCWG)
Development work has allowed advancements on tropospheric and stratospheric chemistry within CAM4. The chemistry is interactive with CAM4 prognostic conditions or with specific dynamics using analyses from meteorological centers, NASA GMAO in particular. Additional developments have

provided a full representation of halogen chemistry within CAM-chem. This has allowed for research on the climate significance of halogen-driven ozone loss in the tropical marine troposphere.

Whole Atmosphere (WAWG)
Whole Atmosphere Community Climate Model (WACCM) developments include improvements in microphysics, the model stratospheric heterogeneous chemistry, the incorporation of halogen chemical processes, and work to diagnose the role of inertial gravity wave forcing on polar stratospheric dynamics and key biases in the Southern Polar Stratosphere. New capabilities have also been added to WACCM to enable new science. WACCM-X has been developed providing a thermosphere and ionosphere extension of the model. A release of this model version is imminent. New capabilities also include a specified chemistry (SC) version of the model in which pre-calculated values of ozone and other radiatively important gases are specified. This greatly reduces the computational cost of the model.

Land (LMWG, BGCWG)
Several model development projects were aimed at reducing biases seen in the Community Land Model, 4 (CLM4). Additional work has provided new functionality in the model. These include the improvement of vegetation processes, cold region hydrology, and soil biogeochemistry. The model now includes methane emissions from wetlands, a prognostic wetland distribution and surface water store, dynamic landunits, ecosystem demography, and a prognostic wildfire parameterization. New capabilities to enable high resolution simulations have been incorporated including high resolution input datasets and a high resolution River Transport Model (RTM).

Sea Ice (PCWG, OMWG)
Numerous enhancements have been incorporated into the Community Ice CodE (CICE) to provide new diagnostic capabilities and enable new grids and ways of running the model (such as interactive ensembles). Development efforts are also underway to assess the influence of subgridscale sea ice heterogeneity on ocean conditions as a part of a collaborative CLIVAR Climate Process Team (CPT) project. This includes an examination of the influence on ocean mixing processes and ocean biogeochemistry in ice-covered waters. Work is also ongoing to improve sea ice simulations in ice-ocean hindcast integrations through an exploration of parameter and forcing sensitivity.

Land Ice (LIWG)
Simulations have been performed to validate the Community Ice Sheet Model (CISM) as a component of CESM. The goal has been to exercise the code and to initialize and validate the model so that CISM can be used for a variety of science applications. This work has included: defining a consistent model grid and boundary condition fields, implementing a procedure to use climate model output to estimate the surface mass balance (SMB) for different elevation classes, and creating a standalone configuration of CESM that allows the ice-sheet model to be forced with previously generated SMB data. This allows for a reduced coupling frequency and allows multi-millennial ice-sheet integrations. Parameter sensitivity tests are underway to determine a configuration that optimizes the steady-state simulation of the Greenland ice sheet when using CESM simulated SMB data.

Ocean (OMWG, BGCWG, Paleo)
Development work with the Parallel Ocean Program (POP) includes the incorporation of new parameterizations for near inertial wave mixing, sea ice heterogeneity effects (both as part of a CLIVAR CPT), and an anisotropic formulation for mesoscale eddies. Resources have also been used to verify the code separation of the mesoscale and submesoscale parameterizations. Parameter sensitivity tests have been focused on reducing biases in ventilation and boundary layer depths. Biogeochemistry work has been performed to incorporate ocean acidification feedbacks and to explore fast spinup techniques for biogeochemistry. Additional work has implemented water isotopes into POP. Enhancements that are

expected in the remainder of the current CSL allocation include the incorporation of improved remineralization schemes aimed at reducing oxygen minimum zone biases. Finally, preliminary integrations have been performed with the Regional Ocean Modeling System (ROMS) that are focused on the coral triangle region.

Infrastructure (SEWG)
Software engineering infrastructure developments have enabled many new capabilities to be incorporated into the CESM. This includes for example, the ability to run multiple instances of a given component, which is being utilized for decadal prediction studies. Additional resources have been used to support new grids, including higher resolution grids, in CESM. Coupling infrastructure has also been improved to handle the flexible transfer of new fields. Ongoing work has used resources to test, load balance, and optimize CESM allowing us to provide a robust system for broad community use on multiple platforms. The model performance has been optimized for multiple resolutions and grid configurations.

b. Scientific Simulations

Scientific simulations have been performed in support of multiple coordinated modeling and assessment activities and to further explore and document processes influencing climate variability and change. These simulations satisfy broad research interests and are being accessed and utilized by a large community of scientists.

Coordinate modeling and assessment activities
CESM integrations have been performed to contribute to the Coupled Model Intercomparison Project, version 5 (CMIP5). This includes the completion of the core CMIP5 experiments with CCSM4 and initialized decadal prediction experiments that were made possible by coupling to the Data Assimilation Research Testbed (DART). Additional CMIP5 20^{th} and 21^{st} century integrations were produced with numerous additional model configurations. This includes runs with the CAM5 atmosphere (CESM-CAM5), runs with interactive biogeochemistry (CESM-BGC) and a prognostic carbon cycle, runs with interactive chemistry, simulations with a dynamic Greenland ice sheet, and coupled integrations with WACCM4. Comparisons across this suite of integrations enable studies on carbon cycle-climate feedbacks, the importance of a high-top atmosphere on 20^{th}-21^{st} century climate variability and change, and projected changes in the Greenland ice sheet mass balance among others. Additional single forcing experiments have been performed to assess, for example, the role of land cover change on 20^{th}-21^{st} century climate.

Simulations have also been performed in support of:

- The Geo-engineering Model Intercomparison Project (GeoMIP) to address several possible geo-engineering methods, including solar reduction and emissions of sulfate in the lower stratosphere. GeoMIP simulations were performed with and without active chemistry. This allows for the investigation of the impact of solar dimming on stratospheric and tropospheric chemistry.
- The Atmospheric Chemistry and Climate Model Intercomparison Project (ACCMIP). These integrations will enable comparisons to observations and are being used to explore chemistry-climate interactions.
- The TRENDY land carbon model intercomparison project. These are being used to explore global and regional carbon cycle response to historic climate change, CO_2 fertilization, and land cover/land use change
- Multiple paleoclimate model intercomparison projects. These include PlioMIP simulations and PMIP3 Last Interglacial simulations. PlioMip is focused on the mid-Pliocene (3 million years ago)

and is designed to explore feedback mechanisms that may have contributed to the significantly warmer North Atlantic and Arctic temperatures at that time as suggested by the paleo-proxy data. The PMIP3 Last Interglacial (LIG) simulations include three intervals in the last interglacial period (130ka, 125ka, and 120ka) (ka: kyrs before present).

Climate variability and change studies
Numerous integrations have been performed throughout the working groups to assess factors that influence climate variability and change. Overall, the numerous simulations performed to investigate various aspects of climate variability and change have provided considerable new insight on issues of detection and attribution, climate feedbacks and processes influencing internal variability. These include a large ensemble of CCSM4 simulations for 1970-2005 to assess issues of detection and attribution for a well-observed historical period. Long control integrations of CAM4 coupled to a slab-ocean-model (SOM) are available, providing a means to investigate the simulated natural variability in the absence of dynamical ocean feedbacks. These are complimented by simulations with specified sea surface temperatures (SSTs) in various regions.

Additional studies are targeted at understanding the role of various processes in the climate response. This includes simulations aimed at investigating the role of Arctic sea ice and freshwater cycle changes on atmosphere and ocean conditions, the role of various factors in the terrestrial response to climate change, the influence of increasing CO2 on the Southern Annular Mode, and the influence of North Atlantic-GIN sea exchange on the Atlantic Meridional Overturning Circulation's (AMOC) deglacial evolution.

Simulations have also been performed to assess the role of non-standard forcings on climate response. These include "nuclear winter" simulations to investigate the influence of a regional nuclear war on climate conditions. A "world avoided" study has also been performed to assess the effects of unrestricted growth of halogen compounds, as might have occurred in the absence of the Montreal Protocol. Simulations have also targeted the impact of aircraft contrail emissions on local cloud fields.

c. Model performance

With the development of CESM1.0, (and subsequent release updates, CESM1.0.1, CESM1.0.2, CESM1.0.3 and the upcoming CESM1.0.4) 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, the development of a new parallel I/O library and its incorporation 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 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.

In addition, the release of CESM1.0 has also been accompanied by the introduction of the CAM spectral element dynamical core, which permits the model to scale out to much higher processor counts than the default FV dynamical core. The above improvements to the CESM have been leveraged to optimize both the throughput and efficiency of experiments and to enable petascale readiness across the CESM model system, an issue of concern raised in previous CCSM CSL proposal reviews.

In what follows, we briefly summarize new CESM performance capability, particularly when targeted to the most computationally expensive CESM configurations. The following figures (courtesy of Pat Worley) demonstrate new high resolution CESM benchmarks that have been carried out in the last year on the ORNL jaguarpf system. Table 1, summarizes the model configurations.

III.	ATM/LND:	0.23x0.31° horizontal grid (1152x768 lon/lat)
	ATM:	FV dycore
	OCN/ICE:	0.1° tripole horizontal grid (2400x3600)
	OCN:	42 vertical levels
IV.	ATM:	0.125° horizontal grid (3,110,402 grid point ne240np4 spectral element cubed sphere grid)
	ATM:	SE dycore
	LND:	0.23x0.31° horizontal grid (1152x768 lon/lat)
	OCN/ICE:	0.1° tripole horizontal grid (2400x3600)
	OCN:	42 vertical levels
a.	B1850_CN: all active components (CAM, CLM, POP, CICE, CISM), pre-industrial, with CN (Carbon Nitrogen) in LND and 26 vertical levels in AT	

Table 1 – model configurations used in high resolution benchmark

Figure (1) below demonstrates the individual component model scaling for configurations IIIa and IVa. The component model performance (measured with coupled runs) is plotted as a function of processor count assigned to that component.

The key performance difference between these two plots is the atmosphere. Other than the atmosphere, the component performance is the same for IIIa and IVa, since land, sea-ice and ocean have the same configurations.

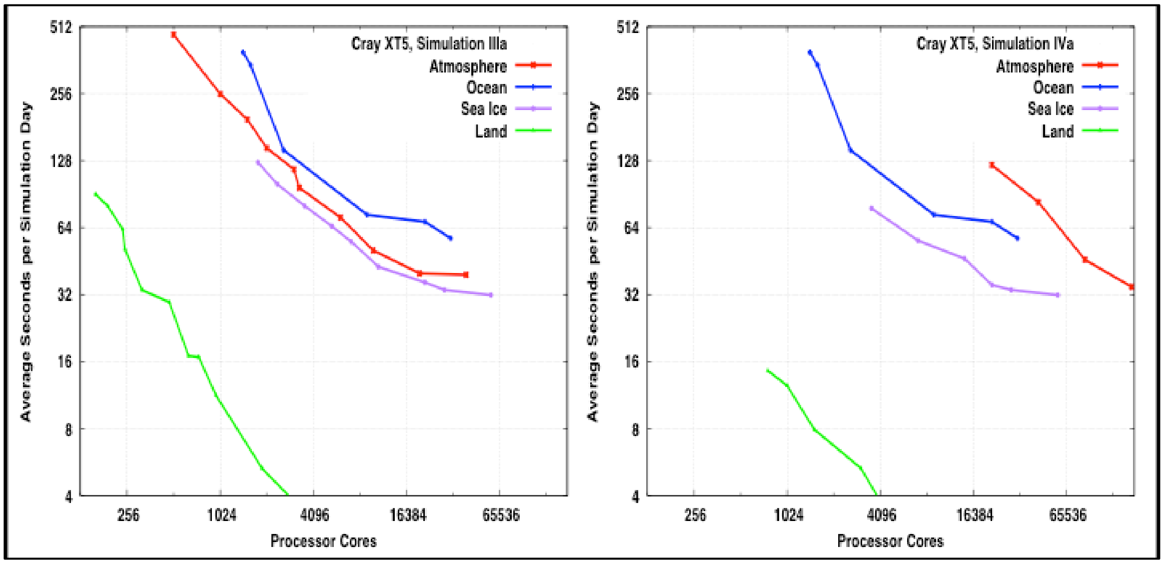

Figure 1 – Component Model Scaling

The key point to note for these two figures, is that the maximum performance of the spectral element (SE) dycore on the 0.125° grid ***exceeds*** that of the FV dycore on the 0.23x0.31° grid. In addition, the performance limiter in the system is now sea-ice, ocean and potentially the coupler.

The high resolution CESM benchmark, shown in Figure 2, provides two views of the same data. Both IIIa and IVa curves include the practical maximum processor count for each configuration. The CAM SE dycore allows IVa to achieve the same maximum throughput of the model system running with an atmosphere running on a 0.125° grid, as the FV system running on a 0.23x0.31° grid. In addition, it was demonstrated that the model system could actually be run out to 200K processors. Given these results, we are confident that CESM is prepared to take full advantage of the new Yellowstone computational capabilities.

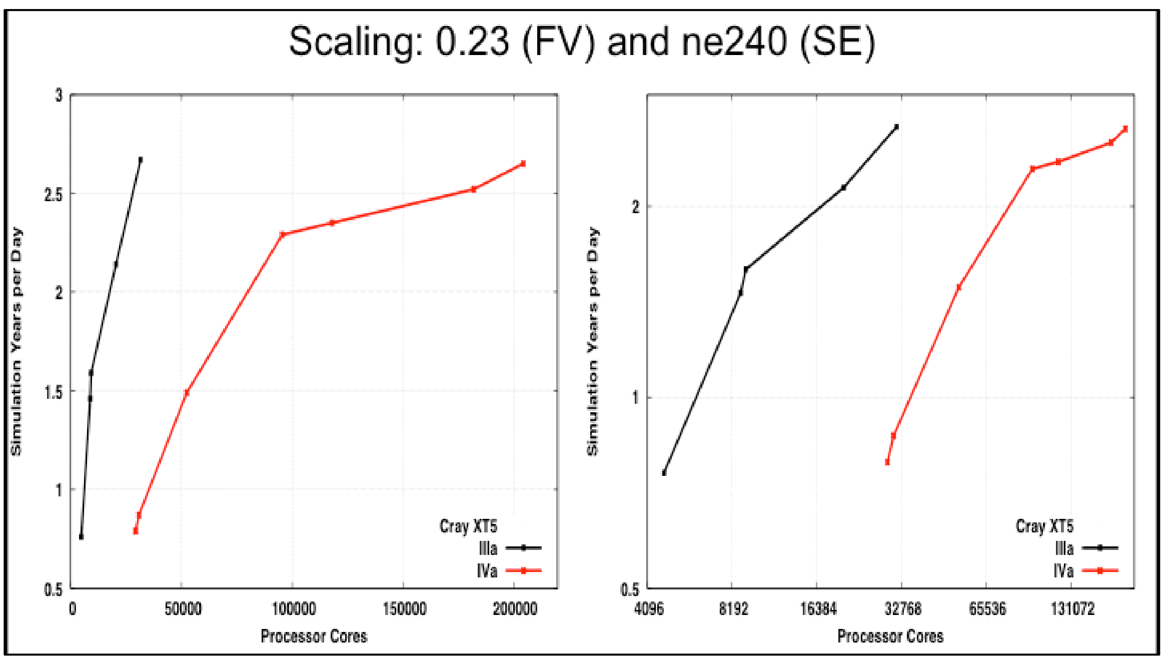

Figure 2 – High Resolution CESM Benchmark – Scaling 0.23(FV) and ne240 (SE)

Overarching Priorities

The full suite of CESM development and production plans extends 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 Climate Process Teams (CPTs) and from the involvement of CESM scientists with university collaborators in agency proposals, including the NSF/DOE/USDA call for decadal and regional climate prediction using Earth System Models (EaSM). Longer-term CESM development activities are also facilitated by the recent DOE proposal "Climate Science for a Sustainable Energy Future" (CSSEF), 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, the CSL resource 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 addition, the enhanced resources available through the NWSC will enable the CESM activity to pursue more ambitious development and production simulations and to remain a leader in earth system model capabilities and advancements. This will allow for improved climate simulation at higher resolution with the inclusion of new processes and model capabilities, and ultimately lead to a better understanding and prediction of global and regional climate.

In what follows, we summarize the overarching development and production priorities across the working group and community project requests. 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 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 model 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.

Note that there is overlap across these priorities with numerous proposed experiments fulfilling multiple development goals.

Coupling across components and understanding interactions

A key attribute of CESM 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.

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. Simulations are also targeted at a better understanding of coupled system biases, including how biases in climate conditions impact biogeochemical cycles. New capabilities will be added across the system that fundamentally include coupled interactions and will require development work in multiple component models. These include the implementation of a global methane cycle and water and carbon isotopes. Additional developments will allow for a more realistic representation of coupled interactions within a smaller set of component models. This includes ocean surface flux developments and ice sheet-land interactions. Finally, simulations are proposed to explore the utility of representing human managed land use changes within CESM for linking to integrated assessment modeling.

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. The incorporation of more earth system components and efforts to run the CESM across a wider range of resolutions, incur unique challenges for parameterization development. A considerable amount of development work is focused on scale-aware parameterizations that will enable the use of new model grids. Working group efforts will also continue to improve the treatment of numerous other aspects of the CESM. These include parameterization developments on sea ice and its overlying snow cover, aspects of the carbon cycle, aerosol-chemistry interactions, sub-gridscale ocean mixing, and land ice albedo. Additionally, new processes will be implemented throughout the modeling system to increase model realism and allow for new feedbacks. This includes new ecosystem processes, subglacial hydrology, and ionosphere physics among others.

High-resolution and new dynamical cores

With increases in computer resources, a societal need for climate information at more regional scales, and scientific questions associated with scale-interactions and high-resolution phenomenon, important development efforts are focused on high-resolution simulations and new dynamical cores that enable these resolutions. These developments are occurring throughout the component models. For the atmosphere, development work will consider global resolutions up to 1/8 degree and regionally-refined grids. Complimentary developments in the land model will enable coupled simulations with these grids. New atmospheric dynamical cores will also be evaluated for the simulation of chemistry and in WACCM integrations for a number of resolutions. In the marine system, development work will include eddy resolving ocean-ice simulations. Nested ocean models will also be further developed to allow high resolution in key regions of interest. For land ice, new dynamical cores will be used that resolve fast flow in ice streams and shelves.

Addressing biases and other known shortcomings

While continued progress has been made over time in reducing model biases, significant shortcomings remain to be addressed. Novel tools, such as data assimilation capabilities enabled by coupling to the Data

Assimilation Research Testbed (DART) and the incorporation of instrument simulator packages (such as the CFMIP Observational Simulator Package – COSP) are providing a new look at biases in the coupled system. Additionally, long integrations with earth system capabilities, such as biogeochemistry, chemistry, and a high-top atmosphere (WACCM), are allowing comparisons to new observational data and are providing unique insight on biases across the coupled system. Work to date has pointed to deficiencies in simulated conditions across working group components. These include shortcomings in land biogeochemistry, the absence of quasi-biennial oscillation (QBO) in equatorial stratospheric winds, biases in CESM hydrology of interest for water management considerations, and biases in the simulation of the polar atmosphere among others. Targeted experiments and developments are proposed to address these. Additional work is proposed to use new tools and new observational data to further investigate biases in the system.

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 on the order of 100 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. With the transition to the NWSC center and the push toward higher resolution simulations, testing in general will become more expensive and performance tuning will take on added significance. Additionally, added model capabilities will enhance the testing needed to fully utilize the CESM system and make it available for community use. In summary, testing is and will continue to be critical for the success of upcoming CESM development efforts and for ensuring the robustness and usability of CESM releases for the user community.

b. Overarching Production Priorities

The production simulations in the more detailed community projects and working group requests (see the appendices) are broadly summarized below in terms of five overarching goals: (1) contributions to nationally or internationally coordinated modeling and assessment activities; (2) benchmark simulations that document components and new capabilities of CESM; (3) climate variability assessment; (4) climate change characterization and detection/attribution: and (5) interannual to decadal prediction experiments. These experiments are of value to the broad community of scientists involved in the analysis of climate simulations. Many of them are cross-cutting activities that involve a number of working groups and we expect that they will be of interest to a large user community. 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. These activities are broad in scope and range from experiments aimed at evaluating and comparing earth system models for various time periods (including paleoclimates) to experiments focused on individual component models or processes within them. For example, resources are requested for participation in multiple paleo-climate model intercomparison projects, assessment activities aimed at studies of chemistry climate interactions, activities devoted to the assessment of numerous terrestrial and biogeochemical processes, coordinated experiments on the influence of solar spectral irradiance variability, experiments designed to addressed the climate consequences of various geoengineering scenarios, and participation in other coupled model intercomparison projects.

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. Many new processes and capabilities are being incorporated into CESM and need to be further assessed. Additionally spin-up runs, for example of the land and ocean biogeochemistry pools, are needed for initializing control experiments.

Climate variability assessment
Earth Systems Models represent a central tool to enhance our understanding of climate variability on multiple time scales. Such characterization requires, for instance, large ensembles of simulations designed to characterize the spread of climate predictions generated by internal variability, studies focused on the role of internal processes in driving climate variations, and experiments to assess the influence of natural forcings in climate variations throughout the historical and paleoclimate records.

Climate change characterization and detection/attribution
Earth System Model experiments provide a means to assess the detection and attribution of recent changes in the climate system and to more generally characterize the role of various anthropogenic forcings on the earth system. Experiments designed to disentangle the role of individual forcings on the historical climate record provide useful insight for these studies as do large ensembles of 20^{th}-21^{st} century climate. This priority is closely related to the assessment of climate variability as discussed above.

Interannual to Decadal prediction experiments
Given an interest in near-term climate prediction, an emerging priority for Earth System Modeling efforts are to improve the understanding of predictability on seasonal to decadal timescales and to advance our ability to realize that predictability. This requires both (1) idealized studies to further understand inherent predictability in the system on these timescales and the factors that can modify that predictability and (2) initialized predictions in both retrospective and future prediction mode in order to test our ability to predict the real system compared to observed conditions. Experiments of both these types are considered here.

Resource Requirements

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 some more specific activities and experiments, as well as the required computing resources. The development and production work being proposed is considerable and here we focus on several examples under each overarching priority. More precise descriptions, and a more comprehensive list of experiments, can be found in the appendices which describe the community projects and the individual working group requests. These 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 below.

Computational estimates for the experiments have been obtained using benchmark simulations on systems that we expect to be similar to Yellowstone or by scaling bluefire GAU estimates by a standard "Yellowstone" factor provided by the Computational and Information Systems Laboratory (CISL). Where experiments are proposed in yet-to-be-available configurations, estimates are based on configurations that we expect to have similar resource needs.

a. Development Activities and HPC Resource Request

Coupling across components and understanding interactions

Water and Carbon Isotope Development

Resources are requested to implement and test both water and carbon isotopes within CESM. This is a joint effort primarily between the paleoclimate and biogeochemistry working groups, but will also involve the expertise of the working groups associated with the component models and software engineering infrastructure. Water isotopes provide a means to understand the modern-day hydrological cycle and our ability to model cloud processes correctly. The carbon isotopes, ^{13}C and ^{14}C, provide insight on numerous aspects of the carbon cycle and provide information on ventilation time scales of the thermocline and the deep ocean. Comparisons to isotopes as measured in ice cores and sediments with paleoclimate integrations provide useful model validation information. Resources are requested to implement and test these isotopes, determine the water isotope response to idealized freshwater inputs to the North Atlantic and Southern Oceans for the LGM and modern climates, and provide simulations for comparison to isotope records from instrumental measurements and paleoclimate records preserved in ice cores, ocean sediments, and caves.

Coupled interactions

Deficiencies in coupled interactions have been noted across CESM. These include a lack of true freshwater fluxes for the ocean model, once-a-day coupling of the ocean model, the potential importance of subgridscale sea ice flux heterogeneity on ocean mixing, deficiencies in river-ocean coupling, and the lack of two-way ice sheet-land coupling. These deficiencies affect the science that can be addressed with the CESM. For example, a lack of true freshwater fluxes in the ocean model component means that issues of sea level rise cannot be adequately studied. Development work will tackle these issues of coupled interactions. In particular, the virtual salt flux approach for ocean freshwater fluxes will be abandoned for more realistic true freshwater exchange; more frequent coupling of the ocean model will be explored, allowing for resolution of the diurnal cycle and inertial periods; a sub-gridscale sea ice flux implementation will be tested for ocean boundary layer calculations; a more physically-based exchange of freshwater through estuaries and coastal river plumes will be implemented, using energetic constraints on the amount and depth of mixing between open ocean seawater and terrestrial freshwater; and two-way coupling between the land ice and land model will be incorporated such that land surface classes can change with changing ice sheet conditions.

Linkages to Integrated Assessment Models (IAMs)

Simulations related to integrated assessment modeling of the role of land use are requested to improve the representation of key land use activities important to the coupling of IAMs and CESM. This link to IAMs represents a new "coupled interaction" not previously considered for CESM, which is facilitated through the newly formed Societal Dimensions Working Group (SDWG). Development resources are requested for improving land model representations of agricultural, forest systems, and ecosystem dynamics. Additional work is proposed to investigate the utility of the representation of these processes within the Community Land Model (CLM) for linking to integrated assessment modeling. This work will involve developing and testing algorithms for translating IAM land use outputs, which often involve different variables and classification systems, into inputs consistent with CLM.

New parameterizations and processes

Scale-aware parameterization developments

Interest in applying CESM to regional climate scales will require model resolutions that span a wide range. In particular, we anticipate that a wide range of spatial resolution atmospheric grids will ultimately be supported - from 2º to 0.25º for both uniform global grids and within the same regionally refined grid. This will require physical parameterizations that can work across these scales and development work will focus on parameterizations that have scale-aware capability. These next generation physics parameterizations include the UNIfied CONvection scheme (UNICON), Cloud Layers Unified By Binormals (CLUBB), cloud PDFs, and atmospheric boundary layer scheme enhancements. All of these have the functionality to more accurately represent and respond to sub-grid scale appropriate variability. Implementations of these individual parameterizations will need to be tested at different scales and will require reasonably long simulations in order to assess their influence on climate conditions.

Improvements in existing parameterizations – aerosol-chemistry interactions

Numerous improvements in existing parameterizations are proposed across CESM component models and processes, as further discussed in the appendices. Here we provide just one example. Development work is proposed to improve the aerosol-chemistry interactions in the context of the currently implement Modal Aerosol Module (MAM). This will include an improved treatment of secondary organic aerosol (SOA) formation and aging, the addition of an ultrafine (nucleation) aerosol mode to more accurately treat new particles from aerosol nucleation, and the separation of primary organic aerosol (POA) by sources (fossil fuel and biomass burning). This will allow for a more realistic representation of chemistry-climate interactions and the influence of primary and secondary organic aerosols on climate forcing

New Processes - Ecosystem Demography

Development efforts across CESM are targeting many new processes that have climate significance. For example, developments within the Community Land Model will incorporate an Ecosystem Demography (ED) approach to vegetation dynamics. This is a statistical approximation of an individual-based forest simulation model, whereby the population of trees in an ecosystem is grouped into cohorts determined by height, plant type, and disturbance history. The recruitment, growth and mortality of representative trees are 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. This represents an important step forward in the realism of ecosystem processes within CLM. Simulations are proposed to explore parameter sensitivity for this new approach and to investigate implications for coupled simulations.

High-resolution and new dynamical cores

Atmosphere

Recent work has implemented the spectral element (SE) dynamical core on a cubed sphere using CAM5 physics (CAM-SE). This core provides vastly superior computation scalability compared to previous dynamical cores, allowing much more efficient use of resources for high-resolution simulations. Simulations are proposed to maintain and improve the scalability of CAM-SE for 0.25^o and 0.125^o grids and to examine the fidelity of potentially high-impact weather phenomenon in high-resolution simulations, including those with regional-refinement. Development work is also proposed to include the infrastructure for physics to be run on a separate grid independent of the dynamical core choice and to implement the Conservative Semi-LAgrangian Multi-tracer (CSLAM) transport scheme, which is more efficient and accurate. These developments will also be tested with interactive chemistry and in WACCM runs at multiple resolutions. Atmospheric vertical resolution enhancements and cloud-resolving super-parameterization developments are also proposed to address high-resolution considerations.

Ocean

To-date, high-resolution ocean simulations (0.1^o) have been performed with earlier ocean model versions. These do not include many of the recent physics improvements of the standard ocean model and do not reflect recent advances in our understanding of adiabatic (submeso and mesoscale lateral mixing) and diabatic (vertical mixing) ocean physics. A series of development simulations are proposed to assess the sensitivity of high-resolution global ocean/sea-ice hindcast simulations to these model improvements. These simulations will also increase the number of ocean vertical levels from 40 to 60 (as in the current coarse resolution ocean model version). Ultimately these simulations will result in an eddy-resolving ocean model with optimal physical parameterization settings for a 0.1-degree model configuration, enabling new science on ocean eddy-resolving influences on climate and marine biogeochemistry.

Land Ice

Development work is proposed to test and implement scalable, higher-order dynamical cores for the Community Ice Sheet Model (CISM). Three dynamical cores have been developed under the DOE Ice Sheet Initiative for Climate Extremes (ISICLES) project. These include higher-order solvers that can simulate fast flow in ice streams and ice shelves, improving on the existing shallow-ice approximation. Development work to implement and assess these dynamical cores includes: the testing of new physical process modules, such as iceberg calving and sub-glacial hydrology; the improvement of basal boundary conditions; performance tuning and scaling tests; verification and validation simulations; the optimization of initial conditions; and tests of the model robustness in high-resolution large-scale standalone simulation (e.g., Greenland and Antarctica at spatial resolutions of 5 km or less).

Addressing biases and other known shortcomings

Biases are present in all aspects of CESM1.0 and their influence propagates throughout the fully coupled system. Here we provide examples of several development efforts aimed at improving biases across the coupled system. These are categorized by model component but are likely to have implications for coupled interactions and thus the climate simulations in general. Further experiments that are targeted at resolving additional model biases and shortcomings are described in the appendix.

Atmosphere

Notable biases are present in the simulation of the polar atmosphere in CCSM4 and CESM-CAM5 with important implications for sea ice motion and mass budgets. The appreciable influence of unresolved parameterized atmospheric dynamics and of stratospheric processes on polar atmospheric circulations and surface wind stress has been increasingly evident in CESM. For example, the Beaufort High, a feature of known importance to Arctic sea ice distributions and variability, is weaker-than-observed in CCSM4 but stronger-than-observed in CESM-CAM5, a difference that is partly traceable to their differing representation of turbulent mountain stress. Simulations are proposed to evaluate the impact of atmospheric dynamic parameterizations including gravity waves and surface stresses, and the sophistication of stratospheric processes on high-latitude climate in CESM-CAM5. Physically based parameterization improvements will be evaluated for their ability to improve atmospheric circulations, with an emphasis on understanding the physics required to improve high-latitude atmospheric circulations and sea ice distributions. Additional atmospheric biases that will be addressed through development work includes: the absence of the Quasi-biennial oscillation (QBO) in equatorial stratospheric winds, precipitation biases of interest for water management applications, and the late breakdown of the southern polar vortex and recovery of ozone among others.

Land

A relatively simple representation of soils is currently present in the CLM, with only one (dominant) soil type represented in each grid cell, and all grid cells held to a fixed soil depth. However, it is well known that soil depth and soil properties can influence local climate conditions and vegetation productivity. Hence we hypothesize that creating more realistic soil depth and soil properties, and linking these to appropriate vegetation types will improve our surface climate simulation especially in wet and dry climate regions. Resources are requested to conduct a number of experiments to incorporate soil more realistically and to evaluate the potential feedbacks associated with these improved parameter settings. Additional shortcomings in the land model that have been identified and will be addressed in CSL development efforts include: land biogeochemistry, including leaf area index, canopy processes, and soil biogeochemistry and the ability to utilize transient land cover change and dynamic vegetation in combination.

Ocean

Arguably one of the most prominent biases in all the CESM coupled simulations is the large surface temperature and salinity errors in the northern North Atlantic Ocean, resulting from the incorrect separation of the Gulf Stream (GS) and the subsequent, too-zonal path of the North Atlantic Current (NAC). To directly address these biases, as a contribution to a collaborative EaSM project, the topographic control of the GS are being investigated with the central hypothesis that processes at the western boundary of the North Atlantic (that include lateral form stress and potential vorticity generation by lateral and bottom topography) exert the primary control on GS separation and the NAC pathway and that these processes are currently either absent or poorly represented in models. Resources are requested to perform a systematic exploration of the GS separation and NAC path to some details of the bottom topography with an ultimate goal of developing new parameterizations to represent these missing physics. Other shortcomings in the marine system that will be addressed using requested development resources include: incomplete snow-cover processes for sea ice, a lack of Langmuir mixing in the ocean boundary layer parameterization, and excessively large oxygen minimum zones in CESM integrations.

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 HPC Development Requests:

Working Group	Development Request (million core-hours)
Atmosphere Model Working Group	9.8
Biogeochemistry Working Group	5.5
Chemistry Climate Working Group	3.1
Land Ice Working Group	5.5
Land Model Working Group	4.8
Ocean Model Working Group	7.0
Paleoclimate Working Group	5.6
Polar Climate Working Group	2.6
Societal Dimensions Working Group	3.9
Software Engineering Working Group	8.1
Whole Atmosphere Working Group	4.9
TOTAL	**60.8**

Note that in the individual requests present in the appendices, simulation experiments have been prioritized as A (highest priority, about 60% of the total request), B (medium priority, about 20% of the total request) and C (lower priority, about 20% of the total request). However, we stress that all of the proposed experiments will fill important development needs and contribute to the overall project priorities.

b. Production Activities and HPC Resource Request

Here we provide examples of production simulations requested for the five overarching production priorities. These span broad research interest and it is anticipated that the output from these experiments will be used extensively by community scientists.

Coordinated modeling and assessment activities

Resources are requested to participate in numerous coordinated activities. These include:
A wide range of Model Intercomparison Projects devoted to assessment of:

- land-atmosphere interactions
- land cover change impacts
- terrestrial hydrological cycle response to climate change
- global and permafrost-carbon feedbacks

Paleo-climate activities, including:

- Paleoclimate Carbon Model Intercomparison Project (**PCMIP**) that combine carbon cycle and paleoclimate modeling with ice-core and paleoclimate records to quantify the carbon-cycle climate feedbacks during the LGM
- **PlioMIP** which will examine the Pliocene climate which had a similar continental configurations and CO_2 concentrations as today but warmer North Atlantic/Arctic conditions and higher sea level
- Paleoclimate Model Intercomparison Project, 3 (**PMIP3**) which will assess a Last Interglacial Transient Simulation from 130 to 110 kyrs ago

A number of activities to assess aspects of chemistry-climate interactions including:

- Chemistry-Climate Model Validation studies (**CCMVal3**) designed to examine ozone depletion and recovery trends
- Coordinated chemistry-climate model experiments with NASA-GISS, which will explore the climate response (including indirect effects) to the regional emission of ozone or aerosol precursors and their subsequent forcing.
- A WCRP SPARC (Stratospheric Processes And their Role in Climate) activity to investigate Atmospheric Processes controlling Stratospheric Sulfur and Aerosols and their Role in Climate (**APSiC**), which will utilize WACCM with the CARMA microphysical model to investigate processes controlling stratospheric sulfate

Simulations in support of:

- **SOLARIS** (SOLAR Influences for SPARC) investigations that are aimed at studying the influence of solar spectral irradiance variability and will utilize the WACCM component
- **GeoMIP** (Geoengineering Model Intercomparison Project), which will allow for the evaluation of the climate and earth system consequences of various geoengineering scenarios
- The Coupled Model Intercomparison Project, 5 (**CMIP5**). While our core simulations for CMIP5 have been completed, additional integrations will be performed with a number of new model features. These include, for example, coupled runs with a dynamic Greenland ice sheet and CAM5 (to compliment similar integrations performed with the CAM4 model) and additional decadal prediction simulations as discussed further below

Benchmark simulations
Numerous benchmark simulations are proposed to explore new model capabilities and physics options. These include:

- Proposed long control integrations with CESM-CAM5 at different atmospheric CO2 levels. This will allow for a robust statistical characterization of internal climate variability and the climate response to external forcing
- Complimentary integrations with the same physical-climate configuration that include interactive chemistry. These will allow for research on chemistry-climate interactions and extreme pollution events
- Coupled control integrations to assess new parameterizations, such as the prescribed modal aerosols and CAM5-SE at a nominally 1-degree resolution
- Different "flavors" of high-resolution benchmark simulations, both coupled and uncoupled. These include multi-century coupled simulations with a $1/4^{o}$ atmosphere (CAM5-SE) coupled to a 1-degree ocean/sea ice model and ocean-sea ice hindcast simulations at a 0.1^{o} resolution. These complimentary simulations will enable studies on high impact phenomena, such as tropical cyclones, and the role of ocean eddies on climate processes and biogeochemistry
- Benchmark simulations with an isotope-enabled CESM
- Reference runs for present day and future Greenland, with CMIP5 and optimal Greenland Ice Sheet (GIS) configurations
- Integrations to assess the value of full coupling (vs. one-way coupling) of an Integrated Assessment Model (IAM) within CESM. This represents an emerging capability within CESM

Climate variability assessment
A number of sets of large ensembles integrations are proposed to characterize and compare the natural variability using different component sets of the CESM. This includes large ensembles of 20^{th}-21^{st} century simulations of CESM-CAM5, CESM-WACCM5, CESM with atmospheric chemistry, and CESM1.5 which we anticipate will be released during the lifetime of this proposal. These will be complimented by a large ensemble of Last Millennium simulations, which will be used to assess decadal to centennial variability in the ocean and atmosphere, and the role of external natural forcings in altering this variability.

Control runs are also needed to robustly characterize internal variability. Long control integrations are proposed with various levels of coupling, including fully coupled simulations, simulations with the atmosphere coupled to the non-dynamic slab ocean, and simulations with specified SSTs. Comparisons of the simulated internal variability across this set will allow for the quantification of the contribution of dynamical air-sea coupling and ocean dynamics to the various patterns and timescales of climate variability. Additional targeted simulations are proposed to investigate the variability characteristics associated with particular processes of interest including the role of volcanic eruptions, solar variability and ENSO on atmospheric variations; the influence of biogeochemical dynamics and feedbacks in past climates; factors that affect variations in the Atlantic Meridional Overturning Circulation (AMOC); and the processes that influence glacial inception.

Climate change characterization and detection/attribution
A number of the experiments discussed above, such as the proposed large ensemble simulations which encompass 20^{th}-21^{st} century climate, will be used in detection/attribution work. Experiments are also proposed that focus on the role of individual forcings on 20^{th}-21^{st} century climate change. This will include regional forcing simulations, for example in which alternative patterns of land use change (as generated by alternative Integrated Assessment Models) will be applied in different regions. Modified

forcing simulations will also be performed, including integrations to assess climate impacts of an increased 21st century methane release, which might result from thawing permafrost. The role of earth system components with inherently long time-scales will be considered in a number of studies, including extensions of future scenarios to examine carbon cycle processes and an exploration of climate model space for future runs to help bracket the potential Greenland Ice Sheet response and sea-level contributions on 100-1000 yr timescales. Finally individual working groups will examine the role of numerous specific factors, such as sea ice loss, on climate changes of interest.

Interannual to Decadal prediction experiments

Initialized decadal prediction simulations with CCSM4 have been performed with ocean initial conditions obtained using assimilation via DART (Data Assimilation Research Testbed). Resources are requested to perform the subsequent assimilation-initialized decadal prediction simulations with CESM (with CAM5 and prescribed aerosols), following the modified CMIP5 protocol. This will include yearly start dates from 1961-2005 with multiple ensemble members. Through comparisons to observed conditions over the recent past, these simulations will provide useful insight on our ability to predict climate conditions on interannual-decadal timescales. Additionally, to diagnose the inherent predictability simulated by CESM, resources are requested for idealized studies to assess Arctic sea ice predictability within the CESM context. These include a control set of short (<10 year) ensemble simulations that are initialized with an identical coupled model ocean/sea-ice/terrestrial state. This will allow for studies on the inherent predictability in sea ice and other conditions. A complimentary set of experiments will investigate the factors associated with initial condition information that can contribute to a degradation of potential predictability in the real system (e.g. a sparse and incomplete observational network and, observational error).

The following table summarizes the individual working groups HPC production requests.

Working Group / Project	Production Request (million core-hours)
Community Projects	39.3
Atmosphere Model Working Group	5.3
Biogeochemistry Working Group	7.8
Chemistry Climate Working Group	7.0
Climate Variability and Change Working Group	12.0
Land Ice Working Group	5.0
Land Model Working Group	4.6
Ocean Model Working Group	4.9
Paleoclimate Working Group	4.8
Polar Climate Working Group	5.1
Societal Dimensions Working Group	5.3
Whole Atmosphere Working Group	13.7
TOTAL	**114.8**

Note that in the individual requests present in the appendices, simulation experiments have been prioritized as A (highest priority, about 60% of the total request), B (medium priority, about 20% of the total request) and C (lower priority, about 20% of the total request). However, we stress that all of the proposed experiments will fill important development needs and contribute to the overall project priorities.

Data Management and Archive Requirements

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 or project:

Working Group / Projects	Development Request (TB)	Production (TB)
Community Projects	0	2129
Atmosphere Model Working Group	297	203
Biogeochemistry Working Group	836	660
Chemistry Climate Working Group	91	427
Climate Variability & Change Working Group	0	350
Land Ice Working Group	40	167
Land Model Working Group	100	108
Ocean Model Working Group	456	258
Paleoclimate Working Group	200	330
Polar Climate Working Group	63	134
Societal Dimensions Working Group	210	196
Whole Atmosphere Working Group	96	377
TOTAL	**1165**	**5339**

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. New tools are being designed and put in place to identify when model data is set to expire and to notify the relevant working group(s). We expect these tools to be in place when Yellowstone comes online and this CSL allocation begins. This will provide an effective means to purge the relevant model data as stated in the following plan.

a. Data Archiving

The total data volume expected from both development and production activities is approximately 6500 Tbytes. All data will be archived on the HPSS. Consistent with increases in requested computational resources, associated with the increase in available resources through NWSC, this represents a considerable increase in data production relative to previous CSL proposals. To manage this data volume we proposed the following archival strategy:

Development: Output data will be stored on the HPSS for a period of at most 36 months after creation, at which point it will be removed, unless retention is requested from the relevant working group co-chairs. "One-off" development experiments will be removed more quickly at the working group co-chair's discretion. We expect that this will account for approximately 10-20% of the development output that is noted above.

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. We anticipate that many simulations, including the community projects will be made available on a shorter timeframe.

c. Data Analysis and Visualization Request
The simulations produced under development and production CSL resources will require considerable analysis and visualization. For these needs, we request access to the Geyser and Caldera data analysis and visualization (DAV) clusters. This will require standard interactive access to these clusters for the working groups members that have CSL HPC resources and for additional participants who are helping in the analysis of these simulations. Currently this includes about 150 participating scientists but is subject to change with changing working group members and involvement.

d. GLADE project file space
We request 300TB of CESM GLADE project space. This will enable efficient access to highly utilized CESM simulation output and forcing data used in hindcast integrations. It will also allow for the post-processing of community project integrations. This is about twice the current CESM project space, which we believe will be necessary given the increased number of integrations and simulation output that will be performed under this proposal. This space will be collectively managed by the CESM working groups.

Summary

Earth System 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 critical 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.

While previous model versions have been critical tools for advancing our understanding of earth system processes, challenges remain. 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. Emerging priorities for regional climate prediction at regional scales requires new production and development efforts to further understanding and simulation fidelity. The development of next versions of CESM is already underway and is a focus of all working groups. This includes advances in new dynamical cores and high resolution capabilities. Experiments are also being conducted to understand the source of biases in existing model versions, 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 175.6 million core-hours (60.8 million core-hours for development and 114.8 million core-hours for production simulations), or 9.75 million core-hours per month, over the period August 2012 through January 2014. 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's leading role in international modeling efforts. All of the proposed experiments will fill important development and production needs and contribute to the overall project priorities. However, note that in the individual requests present in the appendices, simulation experiments have been prioritized in the event that a reduced allocation is awarded.

Appendices

What follows are the resource requests for community projects, which span the working groups, and for the twelve individual working groups. We note that these were prepared by the working groups and refined/revised through a process of iteration and coordination across the groups and with the CESM Scientific Steering Committee (SSC). All of the requests follow the same structure as the main proposal. The level of detail varies across the different requests reflecting the approach of different groups. Computational estimates for the experiments have been obtained using benchmark simulations on systems that we expect to be similar to Yellowstone or by scaling bluefire GAU estimates by a standard "Yellowstone" factor provided by the Computational and Information Systems Laboratory (CISL). Where experiments are proposed in yet-to-be-available configurations, estimates are based on configurations that we expect to have similar resource needs. Although all the runs proposed will fill important development and production needs and contribute to the overall project priorities, we have prioritized runs as A (high priority), B (medium priority) or C (lower priority). "A" runs correspond to about 60% of the overall request, and "B" and "C" runs each for 20%. Where a priority is listed with more than one letter, it indicates that a fraction of the runs (or numbers of years for an individual run) is subject to change to fulfill priority requirements. We note however, that all of the resources requested meet many important needs and contribute to critical development and production science efforts.

In the tables that follow each individual request, the model configuration is listed using the following CESM naming conventions: “B” runs are fully-active coupled components, “BG” runs are fully-active coupled components with a dynamic ice sheet, “C” runs are active ocean with prescribed atmosphere and sea ice, “D” runs are active sea ice with other components prescribed, “E” runs have active components but a slab-ocean-model (SOM), “F” runs are active atmosphere with prescribed surface conditions, “G” runs are active ocean-ice simulations with prescribed surface forcing, “I” runs are active land simulations with prescribed atmosphere forcing.

Community Projects

Research Plan and Broad Science Objectives

This new category of simulations recognizes that there is a class of integration that require significant computer resources and that have a broad appeal across the CESM project. These integrations can be used to address numerous scientific questions and have applications across the CESM working groups. We anticipate that the simulations proposed here will be used extensively by a broad community of scientists for many different scientific applications. As such, these simulations are a component of the Production Runs and meet a number of the overarching Production objectives specified in the main body of this proposal. The specifics of these studies were devised by teams that included numerous working group co-chairs, scientific liaisons, and individual working group members. The simulations outlined here address principal scientific challenges of Earth System Modeling, including how to interpret recent and projected climate change in the presence of natural climate variability, how to understand past climate by combining climate simulations and climate reconstructions, and how to expand the potential of global climate simulations to provide useful information on regional and finer scales.

Production Objectives

The simulations proposed here fall into three broad categories which will allow unprecedented studies on climate variability and change and a benchmark control integration with high atmospheric resolution. The specific categories include:

<u>Large Ensemble Study</u>

This is targeted at the 20th-21st century and will allow investigations on:

- The detection and attribution of climate changes over the 20th-21st century,
- An assessment of the natural variability in numerous aspects of the system,
- Assessments of the changing likelihood of extreme climate events.

Research on the influence of different earth system processes will be enabled by ensemble sets with different model configurations.

<u>Last Millennium Ensemble Study</u>

These simulations will focus on 850-2005AD. They will be used to address numerous science questions including:

- The detection and attribution of climate changes over the last millennium, including Medieval versus Little Ice Age changes in climate;
- Interpretation of thermodynamic and dynamic mechanisms that explain regional responses suggested in proxy synthesis;
- Decadal to centennial variability in the ocean and atmosphere, and role of external natural forcings in altering this variability;
- Assessment of “top-down” influences of solar variability and volcanic aerosols.

High-Resolution Control Integration

With the computational resource enhancements coming online at the NCAR-Wyoming Supercomputing Center (NWSC), there is an unprecedented opportunity to run climate-scale integrations with much higher resolutions. Simulations at $1/4^o$ atmospheric resolution have been tested by the AMWG using CAM5 and show many realistic characteristics in the simulation of high impact weather. For example, simulated Atlantic tropical cyclones exhibit realistic vertical structures, storm tracks and distribution of storm strengths, including category 5 storms. Here we propose to perform a multi-century coupled simulation with $1/4^o$ atmosphere coupled to a 1-degree ocean. This will enable studies on numerous aspects of the climate system.

Proposed Experiments and Computational Requirements

P1. Large Ensemble Study

At the core of this experiment is a large 40-member ensemble of a released version of CESM (the CESM-CAM5). Three additional, smaller (10-member) ensembles are requested with different model configurations including (1) the addition of tropospheric and stratospheric chemistry, (2) the use of WACCM5 (at 2-degrees) and (3) the CESM1.5 model which we anticipate will be released during the life of this proposal. These additional ensemble sets will allow for investigations into how changes in the model influence the variability and change simulated by CESM. Direct comparisons to the large 40-member ensemble will enable for a quantification of the role of enhanced chemistry-aerosol interactions, a high-top atmosphere, and new model capabilities, for example in the land component, on the climate characteristics. All experiments will be run from 1950-2099. For the 21st century, the RCP8.5 forcing scenario will be used.

P2. Last Millennium Ensemble Study

At the core of this experiment is a 10-member ensemble of the CESM-CAM5 at 2-degree resolution with the CMIP5 full forcings (greenhouse gases, solar variability, volcanic eruptions, orbital changes, and land use). We also propose to run 4-member ensembles for greenhouse gases, solar variability, and volcanic eruption forcing each alone, plus as single experiment for the single forcings of land-use changes and orbital changes. Because of the still-debated uncertainty in the amplitude of the solar forcing over the last millennium and into the future, we will also run a CESM-CAM5 experiment with the solar forcing increased by a factor of two. To assess upper atmosphere and chemistry effects, a two-member ensemble with WACCM5 is requested.

P3. High Resolution Control Integration

This integration will use the computationally scalable spectral element dynamical core (CAM-SE) at $1/4^o$ resolution coupled to a 1-degree ocean and sea ice model. We request resources for 300-years of integration.

Experiment	Model Configuration	# runs	# of years	Core hour / year	Total in million core-hours	Total data volume in TB	Priority
P1. Large Ensemble-CORE Set.	B,BGC,CAM5 (0.9x1.25_gx1)	40	150	1080	6.5	300	ABC
P1. CHEM Set.	B,CAM5 CHEM+ (0.9x1.25_gx1)	10	150	1940	2.9	75	ABC
P1. WACCM5 Set.	B,WACCM5 (1.9x2.5_gx1)	10	150	870	1.3	6	ABC

P1. CESM1.5 Set	CESM1.5 (0.9x1.25_gx1)	10	150	1200	1.8	75	C
P2. Last Millennium Ensemble - Core Set.	B,CAM5 (1.9x2.5_gx1)	10	1155	280	3.2	215	AB
P2. Single Forcings Set	B, CAM5 (1.9x2.5_gx1)	14 (4 each of: GHG, Solar, Volcanic) (1 each of: Orbital, Land-use)	1155	280	4.5	300	ABC
P2. High solar single forcing	B, CAM5 (1.9x2.5_gx1)	1	1155	280	0.3	20	ABC
P2. WACCM5 Set	B, WACCM5 (1.9x2.5_gx1)	2	1155	870	2.0	10	AB
P3. High-resolution Control	B, CAM5-SE (ne120np4_gx1)	1	300	56000	16.8	1128	AB
TOTAL					**39.3**	**2,129**	

Atmosphere Model Working Group

Research Plan and Broad Overview Objectives

The goal of the Atmosphere Model Working Group (AMWG) is to develop, release and support the Community Atmosphere Model (CAM) for use as part of the Community Earth System Model (CESM). CAM aims to integrate the most accurate physical, dynamical and biogeochemical representations of the earth's atmosphere to be 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. Increasingly the emphasis is on providing capability to address regional climate research problems in the context of global climate simulations. Proposed simulations not only support core modeling activities specific to AMWG, but also coordinated, across working group activities and funded earth system research projects involving university and other non-NCAR partners e.g., DOE (SciDAC, CSSEF, ASR) and NSF (CPT, EaSM).

Development Objectives

The overarching development goals of this CSL request is to perform model simulation to analyze, validate and further develop CAM5. Analysis will focus on new process interactions and climate sensitivities that have emerged in the most recent analysis of the CAM5 climate. Validation will focus on mean climate and variability, climate statistics and high impact phenomena across the suite of CAM configurations. Development of the physical process representations will focus on improving existing CAM5 parameterizations and advancing nascent parameterization efforts aimed at providing scale-aware utility. For the dynamical core and model infrastructure the focus will be on providing high resolution model configurations capable of addressing regional climate research questions. The AMWG will continue to address the strategic, community and scientific objectives summarized in the AMWG Community Atmosphere Model (CAM) Strategic Plan. Specifically we are requesting resources to address the following development goals:

- Extending the capability in CAM to investigate regional climate problems using globally uniform resolution and global grids with regional resolution refinement

- Improving existing physical parameterizations and incorporating new parameterizations formulated to work across horizontal and vertical resolution variations
- Advancing our knowledge of atmospheric dynamical and physical process interactions and their regional and temporal dependencies in CAM
- Understanding and reducing systematic model errors and model uncertainty using established and novel simulations configurations

The transition to the spectral element dynamical core on a cubed sphere using CAM5 physics (CAM5-SE) is largely complete. A remaining task is the robust specification of boundary datasets and applying them independently of dynamical core choice. Chief among these datasets is orography. CAM requires specification of the mean orography and sub-grid orographic information is used by the gravity wave drag and turbulent mountain stress parameterizations. CAM simulations can therefore exhibit significant sensitivities to the specification of the underlying surface. Alternate dynamical core options including the Model for Prediction Across Scales (MPAS) and the capability to separate transport, physics and dynamical computation grids will provide increased flexibility to robustly test and examine physics dynamics coupling sensitivities.

CAM-SE provides vastly superior computation scalability compared to previous dynamical cores and allows much more efficient use of resources for high-resolution simulations. A priority of AMWG is to advance high resolution capability in CAM toward the 10 km grid-scale resolution. These simulations are feasible with the current hydrostatic CAM-SE dynamical core either through globally uniform or regionally refined high-resolution simulations. High-resolution simulations have the potential to usefully address regional climate problems, but they exercise the physical parameterizations at resolutions they were not designed for and resolve physical-dynamical interactions not previously encountered. Significant diagnosis of the mean climate and variability in high resolutions will play a large role in high resolution model development.

The continuous development of the physical parameterization in CAM remains an important task. Existing CAM5 parameterizations need to be improved and upgraded based on diagnostics of the model climate and process interactions. The Morrison Gettelman (MG) microphysics needs to be included within the convection parameterizations. Currently, the microphysical approximations in the convection schemes are very simplified requiring the number concentration of detrained ice and liquid particles to be specified. Not predicting the number concentration of detrained cloud particle excludes potentially important process sensitivity to climate change. Therefore the MG microphysics will be extended to the convection parameterizations. In order to more completely understand the cloud indirect impacts of aerosols its effects will also be separated between ice and liquid cloud particle changes.

Finally, nascent research efforts to produce physics parameterizations that are scale-aware will be advanced toward production level status. This includes implementations of the Unified Convection Scheme (UNICON), the Cloud Layers Unified By Binormals (CLUBB) and PDF cloud macrophysics schemes. These implementations are being developed to work seamlessly across grid-scales by operating on the inherent scales of the underlying cloud processes being modeled. Supporting these activities will significantly advance the capability to support climate simulations using a range of uniform and regional-refined resolution grids.

Production Objectives

Community acceptance of new model configurations requires a number of CMIP-class experiments to compare with existing released configurations and assess mean climate, climate variability and climate sensitivity statistics. The core objectives of the AMWG CSL production request are as follows:

- Coupled climate validation with the CAM-SE dynamical core
- Global and regional climate validation using a high-resolution version of CAM-SE
- Climate validation using a prescribed aerosol capability in CAM5 (CAM5-PA) at standard CMIP resolutions
- Initial mean climate validation of CAM-FV and CAM5-SE using next-generation physics parameterizations (including UNICON, CLUBB and cloud PDF approximations)

CAM-SE was released as a functionally supported dynamical core in CCSM4 and CESM1, but not as a scientifically supported option. Initial fully coupled simulations have been performed using CESM(CAM5-SE), but the default simulation configuration is not yet finalized. When the specification of boundary forcing data sets has been finalized the goal will be to produce long coupled simulations in order to support periodic releases over the period of the proposal with what is intended to be the default model configuration for production.

With the ongoing development in increasing horizontal and vertical resolution, climate length simulations have to be examined in order to assess mean climate sensitivity to resolved gird scales. Development simulations will address shortcomings on shorter timescales at regional scales, but CMIP class simulations are required to examine the global mean climate to ensure competitiveness and hopefully to document significant improvements compared to equivalent low resolution simulations.
For the lifetime of this proposal AMWG is committed to providing a less-expensive (by a factor 2) configuration of CAM5-FV at and 1º and 2º resolutions. This will require fully coupled simulations in order to compare climate equivalence with the more expensive predicted aerosol version of CAM5. Although, this reduces the fully interactive functionality for the analysis of cloud-aerosol-radiation processes newly implemented in CAM5, it is hoped it will reproduce a similar large-scale mean climate, in a model configuration more useable by individual PI-driven projects where resources for computing are limited.

The final objective is to make production ready the more nascent physical parameterization developments activities central to the development resource request. In the short term it is expected that UNICON and convective microphysics developments will require long coupled simulations to analyze the impact on mean climate. In the longer term currently less mature efforts including CLUBB and PDF cloud schemes will require similar coupled simulations.

Proposed Development and Computational Requirements

Development Experiments

D1. Maintain and improve scalability of CAM at high resolution

We will perform ongoing simulations to maintain and improve scalability of CAM and CESM in order to efficiently and fully utilize CSL resources for cutting edge resolution simulations. In collaboration with SEWG and using both CAM-SE and, potentially, CAM-MPAS we will perform periodic simulations at 0.25° and 0.125° with CAM5 totaling 20 years. Simulations will be performed following dynamical core and physical parameterization code changes that may significantly impact (increase or decrease) scalability. Approximately 5 years of coupled simulation years using CAM-SE will be required to monitor and maintain scalability of a future high-resolution coupled system.

D2. Support separate isotropic grids for physics and transport computations

We will perform simulations to test a separate computation grid for CAM physical parameterizations. Currently in CAM physical parameterizations compute thermodynamic tendencies on the same grid used by the dynamical core. In CAM-SE the quadrature grid in each element is highly irregular meaning that the dynamics state that is passed to the parameterizations is sampled on an irregular grid. The effects of this non-uniformity on the accuracy of the tendencies are unknown. Through a DOE SciDAC funded effort the capability of running physics on an equi-angular gnomonic cubed-sphere grid is being added to CAM-SE. This grid is isotropic to approximately 10% as opposed to the spectral element grid where the physics "control volumes" vary by more than a factor of two. This will enable the physics to be run on a coarser, similar, or finer resolution grid as compared to the CAM-SE dynamics. These simulations will also develop the infrastructure for physics to be run on a separate grid independent of the dynamical core choice. Robust implementation and the effect on climate must be assessed through various simulations of increasing complexity. This effort will require approximately 100 years of CAM5-SE 1º simulation equivalent.

D3. Implementing the Conservative Semi-LAgrangian Multi-tracer (CSLAM) transport scheme

We will perform development, scalability and validation simulations in support of several DOE SciDAC funded efforts to implement CSLAM into CAM-SE. The primary motivations for this effort are to improve the accuracy and efficiency of tracer transport. State-of-the-art climate models incorporate an increasing number of prognostic tracers to accommodate modern microphysics packages, increasing complexity of online chemistry, etc. Already now the computational cost of the dynamics is dominated by tracer transport and adding more prognostic tracers will only augment this trend. Much of this development work will be performed in collaboration with Chem-ClimWG who requires high capacity and efficiency for tracer transport. The CSLAM scheme allows for much longer time-steps than CAM-SE advection algorithms and is expected to be the main driver for improved efficiency. The CSLAM scheme also has certain accuracy advantages, in particular, superior filters to enforce shape-preservation and ability to preserve correlations between tracers. When the implementation is complete the CSLAM transport will be validated. This effort will require approximately 200 years of CAM5-SE 1º simulation equivalent, given the testing requirement of including chemistry and the associated significant increase in computation due to more advected tracers.

D4. Test increases to CAM vertical resolution

We will perform scoping experiments aimed at implementing and evaluating increases to vertical resolution in CAM. The CAM4 physics package had a significant sensitivity to increased vertical resolution due to spurious interactions between the shallow convection, planetary boundary layer and layer-cloud parameterizations. This prevented systematic testing of increased vertical resolution. CAM5 has shown significantly less sensitivity to increasing vertical resolution in initial experiments. The finest CAM horizontal resolution has recently decreased from around 200 km to 12 km, during which time mid-tropospheric vertical resolution has remained at around 1 km. As a consequence the mid-tropospheric aspect ratio has decreased from approximately 0.005 to 0.08. Numerically, further increases in horizontal resolution while maintaining the existing vertical resolution could invalidate the shallow atmosphere and hydrostatic assumptions of the dynamical core governing equations. Strategies will include providing increased resolution uniformly, in the boundary layer near the surface and near the tropopause and higher. Simulations to test vertical resolution at CAM5-SE 1º are expected to require approximately 100 years of simulations. More limited testing at 0.25° is expected to require 10 years of simulation.

D5: Testing regional resolution refinement of global grids in CAM-SE

We will perform several sets of experiments to implement and test regional resolution refinement of global computation grids in CAM. These simulations will support science associated with several funded and upcoming regional climate proposals including DOE/NSF/USDA Earth System Modeling (EaSM), DOE SciDAC and DOE Climate Science for a Sustainable Energy Future (CSSEF). Options for the location and extent of any regional gird refinement are numerous, and application dependant. Therefore, we will focus on three regions that encompass three different climate regimes. The initial focus has been on generating and testing regional refinement over the western United States using CAM-SE. In collaboration with the LMWG we intend to perform simulations testing the optimal configuration of the refinement in order to address the regional climate variation associated with land-atmosphere coupling, mesoscale convective organization and regional climate change. A second focus will be on multi-scale convective organization in the tropical Pacific and in collaboration with the OMWG we will test resolution refinement in the western tropical Pacific to examine convective organization, convectively coupled wave propagation and the modulating impact of atmosphere-ocean coupling. With the near-isotropic resolution coverage in the Arctic that CAM-SE now provides we will collaborate with the PCWG to test a regionally refined mask centered at the pole and extending to cover the annual sea-ice edge maximum. Simulation resolutions will nominally be 1° in the majority uniform part of the global grid, increasing to a maximum of 0.25° and in some case 0.125° in the regions of refinement. We will require approximately 50 years of simulation with CAM5-SE to test North American refined grids and 25 years to test each of the tropical west Pacific and Arctic grids. A subset of these years will be run fully coupled with POP2 at 1° for the West Pacific and Arctic grids. The cost overhead of these simulations is challenging to estimate, but current experience indicates that a 0.125º refined region that covers approximately 2% of the globe consumes double four times the resources of a globally uniform 1º due to the increased number of grid points and decreased timestep interval.

D6. CAM-MPAS validation

CAM-MPAS is a DOE funded and cross-division NESL development activity that has led to an initial implementation of the hydrostatic and non-hydrostatic dynamical core versions into the CESM infrastructure. Further simulations are required to test the final implementation of the hydrostatic configuration and to understand the model response to the non-hydrostatic implementation; a priority for future climate simulations at resolution below 10 km. This activity is expected to require approximately 20 years of CAM5-MPAS 1° simulation years at a similar cost to the equivalent CAM-SE configuration.

D7. Finalize a prescribed aerosol version of CAM5

We will use CAM simulations to finalize a configuration with CAM5 using prescribed instead of predicted aerosols. The current procedure has been to optimally combine in-cloud and grid mean aerosol values depending on liquid cloud fraction. However, there are potential problems when using this procedure in the very high-latitudes due to very low aerosol values from CAM5 derived data. These simulations are intended to provide a prescribed aerosol application procedure that best maintains the fully coupled high-latitude climate seen in CAM5 experiments using predicted aerosols. It is expected that 50 years of prescribed aerosol CAM5-FV 1º simulations will be needed for the final procedure development and a further 20 years of CAM5-SE to test implementation with spectral element dynamical core.

D8. Validating high resolution impactful phenomena

Separate simulations will be performed to examine the fidelity of potentially high-impact weather phenomenon in CAM-SE high-resolution simulations. Existing 0.125° CAM5-SE simulations resolve significantly more detailed and seemingly accurate weather phenomena including tropical cyclones, mid-latitude frontal precipitation and orographically generated precipitation systems. Simulations will be used to validate these features against observations, document changes in the relative contribution of resolved versus parameterized physical and diagnose the role of physical-dynamical coupling. Current areas of concern in the simulations of high resolution impactful phenomena are the scale appropriateness of the parameterized physics and its sometimes spurious impact with the resolved scale dynamics. Simulations of CAM5-SE at 0.25° for 20 years and at 0.125° for 5 years will be required.

D9. Advancing scale-aware physics: UNICON, CLUBB, boundary layers and cloud PDFs

In anticipation of supporting a wide range of spatial grid scales from 2º to 0.25º in separate uniform grid global simulations and within the same regionally refined grid global simulation, computation time will be required for the continued development of physics parameterizations that have scale-aware capability. The schemes that will continue to be developed are UNICON, CLUBB, the University of Washington (UW), boundary layer scheme and PDF representation of macro-physical processes. All of these schemes have the functionality to more accurately represent and respond to sub-grid scale appropriate variability. Implementations of these individually will need to be tested at different uniform and regionally varying grid-scales. This will require approximately 200 years of CAM5-SE 1º simulation time, 15 years of CAM5-SE 0.25° simulations time and 10 years of CAM5-SE regionally refined 1° to 0.25° simulations time.

D10. Advancing cloud microphysics

Cloud microphysical processes will be updated in CAM5 in order to address a number of current deficiencies. Shallow and deep convection parameterizations currently retain very simple microphysical representations and detrained water has a specified ice or liquid number concentration and associated droplet/crystal size. Simulations will be run to test the implementation of an existing version of the deep convection microphysics and ultimately it will be merged with the existing large scale implementation of MG. Precipitation species are currently diagnosed in CAM5, but sub-cycling of the computations and the implementation of cloud sub-columns will enable CAM to predict precipitation species. Specific improvements to ice-cloud microphysics (including droplet activation mechanisms and the separation of ice and liquid cloud) are also required in order to separate indirect effect contributions from different cloud types and water phase. This development work will initially require 200 years of CAM5-FV 2° simulation time with the addition of 100 years of CAM5-SE 1° simulation time later in the proposal period.

D11. Implementing the multi model framework (MMF) into CESM

Simulation time will be used to continue the implementation of the super-parameterization(SP)/Multi Model Framework (MMF) configuration into CAM-SP. Although versions of this configuration exist they are not robustly implemented into the CESM framework in a manner that will ensure future capability and flexibility with other model infrastructure and surface model components. CAM-SP simulations are approximately 50 times more expensive than standard CAM5-FV simulations. It is expected that ongoing testing of CAM-SP will require approximately 20 years simulation, initially at 2° with a more limited set of experiments at 1º requiring 5 years of simulation time.

D12. Investigating physics, dynamics and numerics interactions using initialized and idealized simulations

Systematic errors in mean climate, process interactions and the simulation of atmospheric modes of variability remain in CAM5. In support of the NCAR-DOE co-operative agreement we will perform a series of idealized aqua-planet simulations and initialized hindcasts using the CAPT framework. Foci for these simulations will be the role of physics, timestepping and timescales on clouds, precipitation and transient coupled features in CAM5. Aqua-planet simulations using CAM5 will be used to identify the relative roles of model parameterizations in establishing the model climate and it's climate sensitivity properties in response to simplified climate change forcings (e.g., SST+2 K, 2xCO_2 and present day minus pre-industrial aerosol burdens). These experiments are expected to require of order 200 years of CAM5-SE 1° equivalent simulation time and 30 years of 0.25° equivalent simulation time. Simulations will also incur an additional 50% output increment for high temporal resolution diagnostics.

D13. Understanding the role of coupled errors in initialized simulations
A novel technique for investigating the role of the atmosphere and interactive ocean coupling on persistent coupled biases such as the double Intertropical Convergence Zone (ITCZ) and the ocean equatorial Pacific cold tongue will require a series of coupled and uncoupled CAPT hindcasts. These experiments will apply a set of restoring or 'nudging' tendencies to the evolving atmospheric model state in order to constrain it closer to observed (in this case the ECMWF analysis). These restoring tendencies will be varied in terms of their strength and can be localized to specific regions in the horizontal (e.g., tropical Pacific) and in the vertical (e.g., above the boundary layer). A set of CAM5-SE 1° simulations (approximately 100 years) and fully coupled CESM(CAM5-SE) simulations (approximately 50 years) will identify the mean response to restoring tendency experiment sets. Targeting the Year of Tropical Convection (YOTC) in 2009-2010 CAPT hindcast experiments will be performed to examine the role of a sub-set of the preceding restoring tendency experiments on hindcasts degradation. With spin-up, this is expected to required 20 years of CAM5-SE at 1° and a more limited set 0.25° simulations totaling 5 years.

D14. Diagnosing climate uncertainty in the CESM Cloud-Radiation-Aerosol ensemble system (CAR)
The Cloud-Radiation-Aerosol ensemble system (CAR) is now implemented into CESM. CAR incorporates the complete cloud-aerosol-radiation packages from seven major modeling centers (including NASA, GFDL, ECMWF and NCEP) and allows a comprehensive sensitivity analysis of the coupled climate response to perturbations in these available packages. We will perform a large ensemble of perturbed parameter experiments to examine the climate sensitivity to choice and parameter selection of cloud-aerosol-radiation package. The full range of sensitivity test and models is currently prohibitive so we intend to focus on perturbed experiments incorporating the NCAR, GFDL and NASA packages. These simulations will require approximately 1000 years of 2º simulations to narrow the optimal configuration of the CAM5-FV package and a further 3000 years to investigate climate uncertainty.

D15. Advancing applications research (aircraft jet contrails)
Emissions from aviation exhaust contain water droplets that freeze to form ice-cloud that can have significant local impacts on the radiation budget. In order to further isolate this impact in CAM and support existing FAA funded activities we will perform a series of horizontal and vertical resolution dependent simulations. Using CAM5-FV vertical resolution will be incrementally increased from 30 to 82 levels and horizontal resolution from 2° to 0.5°. A current climate and future climate scenario will be used. This is expected to require 20 years of simulation at each horizontal and vertical resolution totaling 180 years.

D16. Next generation algorithm preparation for GPU utilization (RRTMG)
We will perform a limited number of simulations in preparation for new Graphical Processing Unit (GPU) computing architecture. GPUs will be available for development purposes on NWSC analysis machines. Also, they will soon be a major component of super-computing on DOE resources and are very likely to be central to the next procurement at NWSC. GPUs are designed to exploit massive parallelism far beyond the relatively simple grid decomposition used currently. Simulations to test parallelism paradigms within the physics and dynamics will be performed. Initially for CAM the Rapid Radiative Transfer Model for GCMs (RRTM) radiation scheme will be the focus which will require the equivalent of 20 CAM5-SE 1° simulation years.

Table for development and production experiments: CAM-SE resolutions are specified as the number of spectral elements per face of the cubed sphere grid. Each element has four Gaussian grid points in longitude, of which three can be considered unique to that element. Therefore, if *ne* is the number of elements on a face then the equivalent equatorial resolution is *ne**3*(4 cube faces). For ne30 this is equivalent to a 1º equatorial resolution since *ne**3*4=360. The following equivalent resolutions for CAM-SE are thus; ne15 (2º) ne30 (1º) ne60 (0.5º) ne120(0.25º) and ne240(0.25). Refined resolutions are specified as the following ne30r120 (1º refined to 0.25º) and ne30r240 (1º refined to 0.125º). Simulations with an asterisk (*) indicate resources estimates for new configurations.

Experiment	Model Configuration	# runs	Total # of years	Thousand Core hours / year	Total in thousand core-hours	Total data volume in TB	Priority
D1. CAM5-SE High Resolution	F(ne240) F(ne120) B(ne120_gx1v6)	12 60 24	1 5 2	450 56 56	450 280 112	15000 18800 7520	AB
D2. Physics and transport grids	F(ne30)	20	100	1.2	120	1260	B
D3. CSLAM	F(ne30)*	20	100	2.4	240	2520	B
D4. Vertical resolution increase	F(ne30,L60) F(ne120,L60)	50 5	100 5	2.4 112	240 560	2520 37600	AC
D5. Regional resolution refinement	F(ne30r120)* F(ne30r240)*	45 5	90 5	2.5 10	225 50	1134 252	AB
D6. CAM5-MPAS implementation	F(ne30)*	5	50	1.2	60	630	B
D7. Prescribed MAM aerosols	F(0.9x1.25) F(ne30)	10 8	50 40	0.5 1.2	25 48	620 504	AB
D8. High resolution phenomenon	F(ne120) F(ne240)	15 5	15 5	56 450	840 2250	48000 64000	B
D9. New physics parameterization	F(ne30) F(ne120) F(ne30r120)	100 10 10	400 10 10	1.2 56 2.5	480 560 25	5040 32000 252	ABC
D10. CAM5 cloud microphysics	F(1.9x2.5) F(ne30)	50 20	200 100	0.18 1.2	36 120	640 1260	A
D11. CAM-SP CESM implementation	F(1.9x2.5)*	20	20	9	180	320	B
D12. Physics, dynamics and numerics	F(ne30) F(ne120)	50 15	200 30	1.2 56	240 1680	3780 4800	ABC
D13. Coupled systematic errors	F(ne30) F(ne120) B(ne30_gx1v6)	12 5 2	120 5 50	1.2 56 1.4	144 280 70	1512 16000 1000	B

D14. Climate uncertainty	B(1.9x2.5_gx1v6)	150	1500	0.28	420	27600	BC
D15. Applications research	F(1.9x2.5) F(0.9x1.25) F(0.47x0.63) (L30,L54,L82)	20 10 3	100 20 6	0.18,0.36,0.54 0.7,1.4,2.1 3.2,6.4,9.6	9,10.8,10.8 8.4,8.4,8.4 6.4,12.8,12 = 88	640 496 545	BC
D16. GPU algorithm preparation	F(ne30)	5	20	1.2	24	252	B
Total					**9.847M**	**296.5**	

Production Experiments

These simulations are intended for the final phase of model development prior to acceptance in supported and released version of CAM. They are also intended to be in support of community intercomparison projects and retained longer-term than development experiments for investigation by the wider CESM modeling community.

P1. Validation of CAM-SE coupled climate

The CAM-SE model version is expected to become the primary supported model configuration by AMWG within the first 12-18 months of the proposal period. This requires a minimum set of IPCC-class simulations to demonstrate fidelity in both atmosphere climate and in the climate of the surface components when in a fully coupled configuration. It is expected that this will required 50 years of AMIP simulation using CAM5-SE 1°, 100 years of slab-ocean model simulation to analysis climate sensitivity and 412 years of fully coupled simulation using CESM(CAM5-SE) also at 1°. This will provide a 200-year pre-industrial control simulation in addition to two 20th century forcing ensemble members.

P2. Validation of CAM-SE high-resolution

High resolution simulations are able to resolve a greater number of phenomena important for impactful weather and regional climate research, but the long-term mean climate has the potential to degrade in the presence of physics parameterizations and numerics developed at much lower resolution. Therefore we will perform a set of AMIP experiments to examine the long term climate. This will require two 25-year AMIP simulations using CAM5-SE at 0.25°.

P3. Validation of CAM5 prescribed aerosols

The prescribed aerosol version of CAM5-FV will be validated using the CMIP5 version of CAM5 at 1º resolution in order to examine average climate and 20th century climate evolution equivalent with CAM5 using predicted aerosols. This will require three simulations (an 1850 control and two 20th century simulations) totaling 412 simulations years.

P4. Validation of physical parameterizations in long AMIP and coupled simulations

We will perform a series of coupled climate simulations intended to validate climate using new physical parameterization schemes. A number of ongoing model development activities addressing new and improved physical representations are expected to mature over this CSL proposal period. These include UNICON, CLUBB and enhancements to the microphysics and MAM parameterizations schemes. These physics changes all have the potential to significantly impact both the local and global energy budgets of the fully coupled system, predominantly through direct and indirect cloud-radiation interactions. For these parameterization schemes to be considered as part of a future standard model version and be released to the community the fidelity of long term IPCC-class simulations needs to be maintained. Simulations cost are particularly challenging for this set of simulations. 200 years of AMIP simulations, 500 years of slab ocean model experiments and 400 years of control coupled simulations using CESM(CAM5-FV) at 1º are estimated. Later in the proposal period 100 years of CAM5-SE 1º and 200 years of CESM(CAM5-SE) simulations will be required.

P5. National Multi-Model Ensemble (NMME) Project

In order to support CESM's participation in the NMME, we request resources to perform seasonal hindcast experiments initialized every month from January 1980 through December 2010, each simulation running for 1 year. This is a collaborative project with the Ocean Model Working Group (OMWG) and here we request resources to complete 1 ensemble member for each of the 372 start dates using CCSM4 at 1º for CAM and POP2. The ocean initial conditions will be obtained from the above assimilation product.

Experiment	Model Configuration	# runs	Total # of years	Thousand Core hours / year	Total in thousand core-hours	Total data volume in TB	Priority
P1. CAM5-SE climate validation	F(ne30) E(ne30) B(ne30_gx1v6)	2 2 3	50 100 412	1.2 1.3 1.4	60 130 576.8	630 1260 8240	A
P2. CAM-SE high resolution	F(ne120)	2	50	56	2800	160000	AB
P3. Prescribed aerosols	B(ne30_gx1v6)	3	412	0.9	370.8	8240	B
P4. New physics (AMIP and CESM)	F(0.9x1.25) E(0.9x1.25) B(0.9x1.25_gx1v6) F(ne30) B(ne30_gx1v6)	10 10 10 5 5	200 500 400 100 200	0.7 0.8 0.9 1.4 1.2	140 400 360 140 240	2480 6200 10560 1260 4000	ABC
P5. NMME experiments	B(CAM4 1.9x2.5_gx1v6)	372	372	0.3	111.6	409	B
Total					**5.329M**	**203.3TB**	

Biogeochemistry Working Group

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 under past, present, and future climates. 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 effect is poorly constrained. A primary objective of the BGCWG 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 BGCWG 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:

- coupling across components and understanding interactions (e.g. atmospheric chemistry and ocean circulation)
- development of new parameterizations and processes often by 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)
- understanding how biases in the climate experiment impact biogeochemical cycles
- software development in the area of continuing research into techniques to spin up biogeochemical tracers in the ocean

Because of the high computational cost of reactive nitrogen chemistry in the atmosphere, it has been infeasible to couple the nitrogen cycles of the atmosphere, land, and ocean to each other. The computational resources becoming available now allow us to perform coupled experiments where the land and ocean nitrogen cycles are coupled to a prognostic atmospheric nitrogen cycle, much like we have done with the carbon cycle. Another interaction with atmospheric chemistry that we intend to explore is the coupling of prognostic terrestrial methane emissions to the atmospheric chemistry module.

Ocean biogeochemistry development is ongoing and we will dedicate some of our computational resources to support this. An example of one of the model processes we will focus on is the remineralization of organic matter. Analysis of our CMIP5 experiments, and subsequent development, has highlighted the role that this process plays in our model bias of having excessively large oxygen minimum zones (OMZs). We will also work on incorporating feedbacks of ocean acidification onto biogeochemical processes, improving our representation of the related alkalinity cycle, and incorporating diagnostic carbon isotope tracers into our model.

Evaluating the impact of biogeochemical and physical developments on the full depth carbon cycle currently requires lengthy experiments, 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.

The computational resources becoming available now allow us perform experiments where comprehensive biogeochemical parameterizations are run with resolved ocean eddies. We will begin to evaluate the effect of resolved ocean eddies on near surface ocean biogeochemical processes and explore how well the currently used eddy parameterizations perform for biogeochemical tracers.

Production Objectives

Production runs address fully coupled carbon cycle experiments and single component experiments with well established models. We are requesting computing resources to address the following overarching production goals:

- New spinups of land and ocean biogeochemistry pools for initializing control experiments
- Coupled control and transient experiments to evaluate the impact of land and ocean model developments on carbon cycle-climate coupling
- Extensions of future scenarios to examine carbon cycle processes that operate on long term scales
- Examination of biogeochemical dynamics and feedbacks in past climates
- Evaluation of biogeochemical interactions with other CESM component models
- Additional fully coupled carbon cycle sensitivity experiments

Analysis of CESM1 carbon cycle experiments that have been performed for CMIP5 has revealed some shortcomings in the simulated atmospheric CO_2: a weak seasonal cycle, a weak response to ENSO and volcanoes, and low uptake of anthropogenic CO_2. The model used in these experiment is now nearly two years old and significant development has occurred in the mean time. We propose to evaluate how these developments, and other that are ongoing, impact the land and ocean carbon cycles, their mean state, seasonal cycle, variability and response to transient forcing.

The mission of the biogeochemistry working group includes examining biogeochemical dynamics in past and future climates. We will explore this in ways that have previously been infeasible because of computational resource constraints.

We anticipate that the coupled nitrogen cycle development work will lead to new control simulations.

Proposed Experiments and Computational Requirements

Development Experiments

<u>D1. Coupled Nitrogen Cycle</u>

We propose a few century length experiments, or more experiments of shorter duration, to investigate coupling of the nitrogen cycles of the land and ocean to an atmospheric chemistry module with full reactive nitrogen. These experiments will run with BGC, CAM5 physics, and CAM's chemistry module. The design of these experiments will be coordinated with the Chemistry Climate Working Group.

D2. Methane

In collaboration with the LMWG and chemistry/climate working, the BGC working group is developing and testing a new methane emission parameterization for wetlands and rice paddies. This model has been developed with Department of Energy computational resources. We plan to evaluate, with CSL resources, the methane model and verify that it can reproduce observed fluctuations in atmospheric methane, using best available information about other sources of methane.

D3. Ocean Biogeochemical Developments

Developments for the ocean biogeochemistry have continued since the freeze for CESM1-(BGC). These developments need to be brought into the CESM trunk and evaluated in standard model configurations. In addition, new developments under consideration need to be implemented and evaluated. We propose numerous century length integrations for evaluation of these developments.

D4. Ocean Acidification & 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 in the ocean model.

D5. Carbon Isotope Developments

We propose allocating computational resources for the development of carbon isotope enabled BGC within the ocean model. The isotopes under consideration are ^{14}C and ^{13}C, which can be used to constrain model ventilation and land-ocean carbon flux separation respectively. Because of the additional tracers, these experiments use non-standard configurations. We are not including long spinups for these experiments, which is particularly relevant for ^{14}C, and are assuming that the spinup techniques mentioned below will allow us to efficiently spin up these tracers. This carbon isotope modeling effort is joint with the PaleoWG. Their computational request is covering land and coupled isotope experiments.

D6. Efficient Ocean spinup technique development

A continuing issue for development work and initialization of coupled experiments 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.

D7. Ocean BGC with Resolved Eddies

We propose initial experiments where ocean biogeochemistry is run with resolved ocean eddies. These experiments will be performed with a model configuration now being developed by the OMWG that will have the same vertical grid as the current $^{o}1$ degree configuration.

Experiment	**Model Configuration**	**# runs**	**# of years**	**Core hour / year**	**Total in million core-hours**	**Total data volume in TB**	**Priority**
D1. Coupled N	B,BGC,CAM5,Chem	3	100	2200	.66	30	A
D2. Methane	B,BGC,CAM5,Chem	1	150	2200	.33	15	A

D3. Ocean BGC Improvements	G-ECO, (gx1)	50	100	170	.85	228	A
D4. Ocean Acid. Devel	G-ECO+, (gx1)*	40	100	200	.80	184	A
D5. ^{14}C Devel	G-ECO+, (gx1)*	10	50	200	.10	23	A
D5. ^{13}C Devel	G-ECO+, (gx1)*	40	100	200	.80	184	BC
D6. Newton-Krylov	G-ECO+, (gx1)*	40	50	250	.50	92	A
D7. BGC w/ Eddies	G-ECO*, (0.1$^{o)}$	1	25	60000	1.5	80	AB
Total					**5.54**	**836**	

Note: The coupled (B) runs will use a resolution of 0.9 x 1.25_gx1.

Production Experiments

P1. New Spinups

We propose to include compute resources in our allocation to spinup ocean and land biogeochemical pools. This purpose of these experiments is to determine the equilibrium state of the model given updated physical and BGC modules. We would perform these experiments once model development reaches release-like milestones. These experiments, while long, do not require an active atmospheric component, which reduces their cost.

P2. New Coupled Control Evaluation Experiments

We propose coupled carbon cycle experiments to evaluate the impact of land and ocean model developments (initially evaluated through uncoupled experiments) on carbon cycle-climate coupling. This includes developments related to physics and biogeochemistry. These evaluation runs would be performed more frequently than the spinups and would not be as long. We anticipate some of these experiments being performed with the CAM5 physics package.

P3. New Coupled Transient Evaluation Experiments

Similarly, we propose to evaluate the impact of model developments on the transient response of the carbon cycle, in 1% CO2 ramping experiments, to evaluate idealized BGC responses and feedbacks between BGC and climate, and in historical and RCP (4.5 and 8.5) experiments, to be able to evaluate the model against observations and with standardized future projection scenarios. We anticipate some of these experiments being performed with the CAM5 physics package.

P4. RCP Extension Experiments

Some of the response of the carbon cycle to climate change occurs on multi-centennial timescales. In order to examine these long timescale responses, we are including 500 year extensions of the RCP8.5 and 4.5 scenarios. These will be performed with our existing model and subsequently with an updated model that will include the CAM5 physics package.

P5. BGC in Past Epochs

There has long been an interest in the BGCWG for running carbon cycles experiments in different geological epochs, e.g. LGM and 6000BP. For each of these epocs, we are including in our request time for exploratory runs, partial spinups, and sensitivity experiments. The study of BGC in past epochs is a joint effort with PaleoWG and our allocation request combined with theirs covers all BGC in past epoch experiments. These experiments will be performed with CAM4 physics.

P6. Coupled Nitrogen Cycle

In addition to the coupled nitrogen experiment that have been included as development, we propose to perform control type experiments based on the development work. We are classifying these experiments as production because of the control nature that they have. These experiments will run with BGC, CAM5 physics, and CAM's chemistry module. The design of these experiments will be coordinated with the Chemistry Climate Working Group.

P7. Miscellaneous Sensitivity

Experiments during previous CSL allocation periods, working group PIs have requested that particular sensitivity experiments that were not envisioned during the writing of the proposal be performed. We are including in this proposal time to accommodate such request, anticipating experiments to be performed with CAM4 and CAM5 physics.

Experiment	**Model Configuration**	**# runs**	**# of years**	**Core hour / year**	**Total in million core-hours**	**Total data volume in TB**	**Priority**
P1. Ocean Spinup	G-ECO, (g,x1)	2	2000	170	0.68	183	A
P1. Land Spinup	ICN	2	2000	10	0.04	5	A
P2. Ocean Eval	B,BGC B,BGC,CAM5	3 3	100 100	440 1200	0.132 0.360	14 16	ABC ABC
P2. Land Eval	B,BGC B,BGC,CAM5	3 3	100 100	440 1200	0.132 0.360	14 16	ABC ABC
P3. New 1% Ramps	B,BGC B,BGC,CAM5	6 6	140 140	440 1200	0.369 1.008	39 46	AB AB
P3. New Hist+RCP	B,BGC B,BGC,CAM5	1 1	348 348	440 1200	0.153 0.418	16 19	A A
P4. RCP Extentions	B,BGC B,BGC,CAM5	2 2	500 500	440 1200	0.440 1.200	46 54	AB C
P5. Different Epochs	B,BGC	2	1200	440	1.056	111	AC
P6. Coupled N	B,BGC,CAM5,Chem	2	100	2200	0.440	20	A
P7. Misc. Sensitivity	B,BGC B,BGC,CAM5	6 6	100 100	440 1200	0.264 0.720	28 33	ABC ABC
Total					**7.772**	**660**	

Note: The runs will use a resolution of 0.9 x 1.25_gx1.

Chemistry Climate Working Group

Research Plan and Broad Overview 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. Simulation priorities are strongly driven by the recent advancement in the representation of physics (CAM5, including the modal aerosol module MAM3) and the inclusion of new dynamical cores (e.g., Spectral Element and Model for Prediction Across Scales). In addition, experience gained during the CMIP5 simulations indicate the necessity for sufficiently large ensembles and long control experiments to identify statistically-significant signals, especially when considering extreme events such as high-pollution associated with heat waves and other stagnant conditions. We will also fulfill our commitments to several model Intercomparison projects: GeoMIP (geoengineering) and Atmospheric Chemistry and Climate.

It is important to note that many of the proposed simulations focus on the fully-coupled chemistry-climate system, hereby moving beyond many of the experiments performed in the previous CSL cycles. We are focusing many of our experiments on the 1° configuration for comparability to CMIP5 simulations and are using the additional available cycles to fully represent tropospheric (and, if needed, stratospheric) chemistry.

Development objectives

- Chemistry in CAM5 SE and FV: simulations to document the performance of SE in transport and mixing, as compared to the FV configuration will be performed under a variety of configurations and resolutions
- Chemistry and modal aerosols: while a preliminary implementation of tropospheric chemistry interaction with MAM3 is being evaluated, we are proposing additional simulations to better represent chemical aspects, with a specific focus on secondary-organic aerosols
- Biases in tropospheric ozone are mostly present near the tropopause and during summertime at the surface. Experiments are planned for identifying the potential for increased vertical resolution in addressing those biases

Production objectives

- Long control experiments with CAM5: these long simulations will provide the necessary statistics to quantify the specific roles of emission and climate changes on chemistry. In addition, these simulations will complement the chemistry experiments included in the Large Ensemble project
- Climate response to regional forcing: the experiments will provide a quantification of the chemistry-climate coupling associated with a specific emission. This is key for the understanding of the relationship between forcing and climate response, including teleconnections
- Model Intercomparison Projects: simulations in support of existing (GeoMIP) and new (Hindcast) projects are included. In the case of the Hindcast Project, in addition to requested simulations, we have included sensitivity simulations to gain a fuller understanding of the driving parameters

Development Experiments

<u>D1. Chemistry in CAM-SE</u>

In order to perform simulations for a SciDAC proposal funded for the exploration of transport properties of SE, we are requesting computing time to perform test simulations of CAM5-SE with interactive chemistry. We will also perform equivalent Finite Volumes simulations to identify differences in the representation of tracer transport and the subsequent impact on chemistry. The results will be analyzed in terms of horizontal and vertical transport of chemical constituents and tracers. The simulations will be performed at a variety of resolutions (up to 0.25°) since SE will be particularly useful for high-resolution simulations. Most of the testing and development of necessary diagnostics and code changes will be performed using the 1-degree versions of CAM5-SE and CAM5-FV.

D2. Chemistry mechanisms

Simulations are proposed to test and evaluate new chemistry mechanisms (i.e. list of reactions); the main targets are

- The Common Representative Intermediates (CRI) mechanism, version 2 (CRI v2), a reduced mechanism describing ozone formation from the tropospheric degradation of methane and 115 emitted non-methane hydrocarbons and oxygenated volatile organic compounds
- An expansion of the isoprene chemistry mechanism to allow for a better representation of OH recycling
- An expansion of night-time chemistry to better represent the morning chemistry (mainly inclusion of $ClNO_2$)

All simulations will be performed with 2° CESM-CAM5 with chemistry.

D3. Exploration of higher vertical resolution

We propose to explore the importance of vertical resolution on boundary-layer ventilation (critical for the transport of pollutants away from the surface) and on transport of ozone (and other chemical species) across the tropopause. For this purpose, we will explore a variety of configurations for the vertical distribution of approximately 100 levels in the troposphere and lower stratosphere. This will be performed using CESM-CAM5 with interactive stratosphere-troposphere chemistry.

D4. Land-use and Secondary-organic aerosols

To better represent the interaction between land and chemistry, we will focus on the following developments:

- Implementation of emissions from land use change scenarios for various RCPs and other scenarios
- Implementation of crop damage from pollution
- Implementation of Yienger and Levy soil nitrogen oxide emissions
- Updating and maintaining BVOC code in the CLM
- Updating and expanding the SOA model in CAM

Most simulations will be performed at 2 degrees, except for item #2 (1-degree).

D5. Modal Aerosols

In the context of further development of the modal aerosol module (MAM) in CAM5, we are requesting computer resources to

- Improve the treatment of secondary organic aerosol (SOA) formation and aging
- Improve MAM by adding additional aerosol modes: an ultrafine (nucleation) mode to more accurately treat new particles from aerosol nucleation
- Separate primary organic aerosol (POA) by sources (fossil fuel and biomass burning) by adding an Aitken primary carbon mode for new emitted POA from fossil fuel combustion

D6. Impact of aviation

Development will focus on enabling the representation of aircraft emissions using different particle size assumption about emitted particles. In particular, a new ice nucleation module is under development and being tested; this will enable us to assess the impact of aircraft aerosols on ice clouds and resulting radiative forcing.

D7. Kinetic energy backscatter scheme

We will evaluate the impacts of the stochastic kinetic energy backscatter scheme on extreme pollution events and separately on dust and biomass burning emissions. Since this scheme perturbs the wind in the boundary layer we expect it to influence dust and biomass burning emissions. In addition we propose here to develop additional stochastic parameterizations targeted at perturbing processes directly relevant for dust and biomass burning emissions if analysis suggests that insufficient variability is seen in the emissions from these processes. We propose the following analysis using the CESM at 1-degree, present-day conditions.

Experiment	Model Configuration	# runs	# of years	Core hour / year	Total in core-hours	Total data volume in TB	Priority
D1. Chemistry in CAM-SE	F, CAM5_STRATTROP (1°) F, CAM5_STRATTROP (0.5°) F, CAM5_STRATTROP (0.25°) F, CAM5_STRATTROP_SE (1°) F, CAM5_STRATTROP_SE (0.5°) F, CAM5_STRATTROP_SE (0.25°)	50 25 10 50 25 10	2 2 2 2 2 2	1600 6400 20000 1800 7200 28800	160000 320000 400000 180000 360000 567000	10 10 10 10 10 10	ABC ABC AB ABC ABC AB
D2. Chemistry schemes	F, CAM5_TROP (2°)	50	10	415	187500	10	ABC
D3. Vertical resolution	F, CAM5_STRATTROP (1°) (100 levels)	10	5	6500	325000	5	A
D4. Land use / SOA	B, CAM5_TROP (2°) B, CAM5_TROP (2°)	10 10	4 1	500 1660	20000 16600	1 1	A B
D5. MAM aerosols	Multiple resolutions				433000	7	A
D6. Aviation impact	Multiple resolutions				80000	1.5	A
D7. Kinetic energy backscatter scheme	F, CAM5_STRATTROP (1°)	1	50	1660	249000	5	B
Total					**3.058M**	**90.5**	

CAM5_STRATTROP refers to the implementation of CAM5 physics, modal aerosols (3-modes) with interactive chemistry valid for troposphere and stratosphere (approx. 125 tracers)
CAM5_TROP refers to the implementation of CAM5 physics, modal aerosols (3-modes) with interactive chemistry valid for troposphere (fixed stratosphere) (approx 100 tracers)
SD refers to Specified Dynamics
SE refers to Spectral Elements

Production Experiments

P1. Chemistry in CAM5: control experiments and 1850-1950 simulation

Associated with the testing and development of interactive chemistry in CAM5, we need to define a long control experiment for 1850 (300 years) with the fully coupled CESM, CAM5 physics and interactive stratosphere-troposphere chemistry (including MAM aerosols). This will be used for the 1850-1950 simulation necessary to define the initial conditions for the chemistry experiments in the proposed Large Ensemble. While it is documented that climate can significantly affect atmospheric chemistry and air pollution in particular, it is usually difficult to disentangle the roles of climate and emissions, especially if interannual variability is large. We therefore propose to perform 4 additional long-term control experiments:

- year 2000 climate, year 2000 emissions (300 years)
- year 2000 climate, year 2100 emissions (100 years)
- 4xCO2 climate, year 1850 emissions (300 years)
- 4xCO2 climate, year 2100 emissions (300 years)

This provides the necessary set of simulations to statistically identify the separate impact of climate and chemistry on a variety of diagnostics, including precipitation and air quality. The longer simulations will be used to identify potential shifts in extremes. For consistency with the Large Ensemble (and CMIP5 simulations), all simulations will be performed with CESM-CAM5 at 1° with interactive chemistry.

P2. Climate response to regional forcing

As demonstrated in recent numerical experiments by G. Branstator and W. Washington, the impact of black carbon aerosols over Asia is not limited to that region but includes an impact on surface temperature over the Southwestern United States. In order to capture that signal (above the interannual variability and climate noise), it is necessary to run the model for approximately 100 years with fixed forcing. We propose here to perform simulations in which *emissions* (of ozone precursors or aerosols) are perturbed to capture the climate response to the direct and indirect forcings. This work will benefit from identical simulations performed by D. Shindell (NASA/GISS) with the NASA/GISS model. Each simulation is for present-day conditions and targets a specific emission (e.g. black carbon) from a specific region. These simulations will be performed with fully coupled CESM-CAM5 at 1° with interactive chemistry. As a consequence, these new simulations can be used to understand regional climate change in CMIP5 simulations associated with changes in emissions.

P3. Methane emissions and climate: last Glacial Maximum

In light of recent discussions on the representation of isoprene chemistry and the associated OH recycling, it is important to revisit our understanding of the methane cycle during the Last Glacial Maximum since much-reduced emissions of isoprene is usually identified as the main driver for the estimated methane concentration. This is also timely due to the implementation of wetlands methane emissions in CLM, forcing a consistency between the simulated methane wetland emissions and the simulated climate. For consistency with the paleo-climate simulations performed for CMIP5, we will use fully coupled CESM at 1-degree with troposphere-stratosphere chemistry.

P4. Hindcast experiments

In support of the Atmospheric Chemistry and Climate activities under the International Global Atmospheric Chemistry (IGAC; see http://igac.jisao.washington.edu/ACandC.php) program, we are proposing to perform a suite of experiments aim at reproducing and understanding the atmospheric composition changes over the last decades, for which we have observations (in-situ and satellite). Proposed simulations include specified-dynamics (using the GMAO MERRA reanalysis products), AMIP-style simulation, sensitivity to emissions, and varying resolutions. These will enable the quantification of the role of accurate meteorology and emissions on observed long-term trends and interannual variability of atmospheric composition since the 1980s.

P5. GeoMIP (in collaboration with J. Meehl)

To continue our support of the Geoengineering Model Intercomparison Project (GeoMIP), we propose to perform two sets of simulation:

- 1-degree CAM4 with interactive chemistry
  - RCP 4.5 (2 ensembles 2020-2100)
  - RCP 4.5 with solar dimming (2 ensembles 2020-2100)

  These are extensions (additional ensembles) to a model run to exploring the impact of solar dimming on tropospheric and stratospheric chemistry in the future. This model run will be compared to a similar model simulation performed without chemistry.
- 1-degree CAM4 with biogeochemistry (in collaboration with K. Lindsay)
  - 1850 control (200 years)
  - 4xCO2 control (150 years)
  - 4xCO2 + solar dimming (3 ensembles of 50 years)

These additional GEOMIP simulations will be compared to existing simulations performed without BGC. This is to identify the importance of ocean acidification in a geo-engineered world.

P6. Land-use and secondary-organic aerosols

The proposed simulations goal is to separate the impact of anthropogenic emissions, natural emissions, long-lived greenhouse gases, and land use change on surface ozone and particulate matter over the United States (focusing on national parks due to the availability of observations). These require specific simulations for each of the sensitivity parameters listed above. In all cases, 10 years simulations are required to improve the signal-to-noise ratio; these are short simulations because the chemical impact is not allowed to feedback on climate. A subset of these simulations will be redone at higher resolution (1-degree instead of 2) to identify potential links between air quality and meteorological extremes in present and future climate.

P.7. Modal Aerosols

The production objectives for the Model Aerosol studies are

- Evaluate modeled primary and secondary organic aerosol concentrations with observational datasets
- Investigate the coupling of volatile organic compound chemistry and secondary organic aerosol formation
- Assess and quantify the uncertainties of primary and secondary organic aerosol treatment on climate forcing

For consistency with the existing CAM5 simulations, all proposed simulations will be performed with CESM-CAM5 at 1-degree.

P8. Data assimilation

This is a continuation of the work on assimilating satellite observations of chemical species in CAM-chem using the IMAGE DART framework. We will assimilate tropospheric ozone retrievals from the IASI and OMI satellite instruments into the CAM-Chem/DART network and investigate the degree to which the assimilation improves the representation of tropospheric composition. We propose to perform 4 sets of simulation (40 members in each case)

- no assimilation
- assimilation of IASI
- assimilation of OMI
- assimilation of IASI and OMI

to identify the potential added benefits of assimilation of multiple species and measurements.

P9. Aviation

The main objective of this study is to assess the impact of aircraft aerosol emission on climate through altering natural cirrus. To gain more confidence on our results and to reduce uncertainties of our estimates, we propose to conduct sensitivity studies by performing CAM5 simulations over various horizontal grids.

Therefore, we will conduct CAM5 simulations under the following resolutions: 2-degree, 1-degree and 0.5-degree. Each experiment will run for 20 years to allow us to examine the statistical significance of the perturbations. Two emission scenarios are considered, i.e. the 2006 observation and the 2050 projection.

Experiment	Model Configuration	# runs	# of years	Core hour / year	Total in core-hours	Total data volume in TB	Priority
P1. CAM5:1850 Control	B, CAM5_STRATTROP (1°)	1	300	2000	600000	30	A, B, C
CAM5: 4xco2 ctrl	B, CAM5_STRATTROP (1°)	1	300	2000	600000	30	A, B, C
CAM5:4xco2 ctrl w/2100 emissions	B, CAM5_STRATTROP (1°)	1	300	2000	600000	30	A, B, C
CAM5:2000 climate/2000 emissions	B, CAM5_STRATTROP (1°)	1	300	2000	600000	30	A, B, C
CAM5:2000 climate/2100 emissions	B, CAM5_STRATTROP (1°)	1	100	2000	200000	10	A, B, C
CAM5:1850-1950	B, CAM5_STRATTROP (1°)	1	100	2000	200000	10	A
P2. Climate Response to regional	B, CAM5_TROP (2°)	20	100	500	1000000	50	A, B, C
P3. LGM-CH4	F, CAM5_STRATTROP (1°)	10	30	1660	498000	10	A, B, C
P4. Hindcast	F, CAM5_STRATTROP (0.5°)	3	5	20000	300000	16	A
	F, CAM5_STRATTROP (1°)	10	20	1660	332000	10	A
	F, CAM5_STRATTROP_SD (1°)	5	30	3320	498000	20	A
P5. GeoMIP	B, CAM4_STRATTROP (1°)	1	320	1400	448000	35	A
	B, CAM4_BGC (1°)	1	500	480	240000	40	A
P6. Land use / SOA	B, CAM5_TROP (2°)	28	10	500	140000	3	A
	B, CAM5_TROP (1°)	6	10	1660	99600	3	B
P8. MAM aerosols	Multiple resolutions				289000		B
P9. Data assimilation	F, CAM5_TROP (2°)	160	1	400	6400	4	B
P10. Aviation impact	Multiple resolutions				250000		
TOTAL					**6.959M**	**426.5**	

CAM5_STRATTROP refers to the implementation of CAM5 physics, modal aerosols (3-modes) with interactive chemistry valid for troposphere and stratosphere (approx. 125 tracers)
CAM5_TROP refers to the implementation of CAM5 physics, modal aerosols (3-modes) with interactive chemistry valid for troposphere (fixed stratosphere) (approx 100 tracers)
SD refers to Specified Dynamics
SE refers to Spectral Elements

Climate Variability and Change Working Group

Research Plan and Broad Overview of Objectives

The goals of the Climate Variability and Change Working Group (CVCWG) are to understand and quantify contributions of natural and anthropogenically-induced patterns of climate variability and change in the 20^{th} and 21^{st} centuries by means of simulations with CCSM/CESM and its component models. With these model simulations, researchers will be able to investigate mechanisms of climate variability and change, as well as to detect and attribute past climate changes, and to project and predict future changes. The CVCWG simulations are motivated by broad community interest and are widely used by the national and international research communities. The CVCWG, which was established this year, merges the previous Climate Change WG and Climate Variability WG. This proposal consolidates resource requests that previously have been separately requested by these WGs.

The types of fully-coupled CCSM/CESM simulations conducted by the CVCWG include simplified forcing experiments, long pre-industrial control runs, large ensembles of 20^{th}-century simulations with various combinations of natural and anthropogenic forcings, and large ensembles of future climate simulations using different emission scenarios. Single-forcing runs, isolating 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 and attribution. Analyses typically target changes in mean climate and associated uncertainties due to natural variability obtained from the large number of ensemble members, changes in variability and extremes, and changes across collections of ensemble members with different scenarios to assess forcing-related uncertainties. We also run and analyze initialized decadal hindcast/prediction experiments to better quantify time-evolving regional climate change over the next few decades.

In addition to fully-coupled model simulations, the CVCWG conducts a broad suite of forced simulations with the atmospheric model component coupled to the land model component of CCSM/CESM (a configuration termed A-L). These A-L model simulations are forced with the observed and simulated evolution of sea surface temperatures (SSTs) and sea ice (the so-called Atmospheric Model Intercomparison Project, or AMIP, protocol) in various ocean basins to allow for a mechanistic understanding of the origin of climate variability and change within the observed climate system and within the simulated CCSM/CESM climate system, respectively. These AMIP-style integrations are also performed with a simple slab ocean model (SOM) in various regions to allow for thermodynamic air-sea feedbacks. For all AMIP-style runs, an ensemble is performed with typically at least 10 members to assess uncertainty. Finally, long (approximately 1000 year) control runs of the A-L model in the absence of SST and sea ice variability beyond the mean seasonal cycle are conducted to assess patterns of variability on a broad range of time scales that are inherent to the atmosphere-land system itself, which has limited predictability beyond a few months. In addition, similarly long control runs of the A-L model coupled to the SOM are conducted to assess what additional patterns and time scales of climate variability originate from thermodynamic air-sea interaction. The simulations performed with such a hierarchy of model configurations allows for a systematic evaluation of the processes governing climate variability, and hence informs our mechanistic understanding of climate variability and change.

Key aspects that help define the nature of the climate-change simulations performed by the CVCWG are the equilibrium climate sensitivity and the transient climate response (TCR), along with contributions of various feedbacks to the response of the model to external forcings. As new model versions become available, the CVCWG 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. As the CESM increases in complexity, analyses by the CVCWG encompass more and more interacting components to help understand and quantify the climate system response.

An important priority for the new CVCWG is to work with the current generation of CESM simulations. Because CESM's basic climate, climate sensitivity, and TCR are evolving from CCSM4/CAM4 to CESM1/CAM5, the CVCWG needs to reassess the implications of this for all aspects of climate variability and change. And because CESM has increased in complexity, CVCWG needs to analyze more interacting components to adequately understand and quantify the climate system response. This analysis makes intense use of computational resources to ensure adequate statistical sampling via long runs or multiple realizations.

The CVCWG 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 CVCWG does not lead 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 with the Biogeochemistry Working Group, the Polar Climate Working Group, and the Paleoclimate Working Group.

Production Objectives

Most of our production objectives target the new physics available in the CAM5 atmospheric component of the CESM. Computing resources are requested to address the following overarching production objectives:
Long control simulations and large ensembles of 20th-century simulations with a hierarchy of model configurations as discussed above to explore patterns, time scales and mechanisms of climate variability and change (P1)
Single-forcing and modified-forcing experiments for the 20th century and future century to assess attribution of climate variability and change (P2).
Overlapping series of decadal simulations to investigate decadal predictability (P3).

(P1) The long control simulations and ensembles of 20th-century simulations address several science questions including: what are the patterns of internally generated climate variability over a broad range of time scales from interannual to centennial; what mechanisms govern this variability; how does low-frequency (*e.g.*, decadal/multi-decadal) variability interact with or influence higher-frequency variability (*e.g.*, extreme events); what are the relative contributions of natural and externally-forced (for example, due to increased greenhouse gases) climate signals? Additionally, it is important to use the long control runs to study the processes and mechanisms that produce decadal and multi-decadal timescale climate variability so we can apply that knowledge to improve decadal climate predictions. Long control runs with the A-L model using specified SSTs can be compared to similar runs with the atmosphere coupled to the non-dynamic slab ocean (SOM) and the fully coupled (CESM) version to quantify the contributions of dynamical air-sea coupling and ocean dynamics to the various patterns and timescales of climate variability.

(P2) Single-forcing runs are necessary for detection/attribution studies to attempt to identify unique patterns of response associated with a particular forcing. These patterns can then be used to search for their contributions in observations to attribute which forcing is causing what part of climate change. Single-forcing runs are also very useful in diagnosing the processes associated with a particular forcing in producing certain regional climate changes. For example, an effective way to isolate the effect of black carbon aerosols' influence on the Indian monsoon is to study the climate-system response to those aerosols in a single-forcing experiment.

(P2) In addition to single-forcing runs, the CVCWG performs simulations with modified forcings designed to explore specific aspects of the climate system. One example is the effects of hurricanes on ocean circulation. Hurricanes (tropical cyclones) have traditionally been perceived as intense but relatively small-scale phenomena, with little effect on the large-scale climate system. However, recent observed evidence has suggested that hurricanes could play a much-more significant role in global climate. The CVCWG proposes to test the effects of the hurricane wind and rainfall in each of the ocean basins: the North Atlantic, North Pacific, South Pacific, and Indian Oceans.

(P3) The new field of decadal climate prediction presents exciting challenges for climate modeling because the entire coupled climate system should be initialized with observations. Then the model is integrated forward in time to attempt to capture the time-evolving statistics of regional climate change. These results are essential for adaptation efforts, and have shown promise in hindcast experiments for being able to capture not only some of the elements of climate over the first decade of simulation, but also patterns associated with external forcing from greenhouse gases after the first decade. A major research question is what the best method for initialization is. A great deal of work has gone into the development of a coupled data-assimilation scheme for initializing decadal prediction experiments with CESM, and there appears to be great promise in such a methodology for improved skill in decadal climate predictions. Recent research has shown that the initial CMIP5 protocol of hindcasts starting every five years from 1960 was not adequate in being able to formulate accurate bias adjustments to allow for model systematic errors. A very recent recommendation to the CMIP5 decadal-climate-prediction protocol has suggested more initial states are desirable, with start dates every year instead of every five years. The CVCWG will carry out the decadal prediction runs mandated by the evolving CMIP5 protocol, and quantify the predictability due to initial conditions and that due to external forcing.

Production Experiments

(P1) The CVCWG proposes to contribute 1500 years toward a total 2000 years of pre-industrial control simulation with fully coupled CESM1(CAM5CN) at 1° resolution (labeled “fully coupled control” in the Table below). We propose an additional 1000-year pre-industrial control run with CAM5 at 1° resolution with prescribed sea-surface temperatures set to a repeating seasonal cycle to isolate variability in the atmosphere (labeled “atmosphere control”), and a 1000-year pre-industrial control run with CAM5 at 1° resolution coupled to a slab ocean (labeled “slab-ocean control”), to further differentiate among sources of variability.

(P1) To investigate variability within the 20th century, we propose three experiments with CAM5 at 1° resolution, each with ten ensemble members. The three experiments have different prescriptions for SSTs (labeled “20th C SST forcings”): one with prescribed observed evolution of SSTs within the tropical oceans (25°N-25°N) during 1900-2010 and a repeating climatological seasonal cycle of SSTs elsewhere; one with prescribed observed evolution of SSTs globally and radiative forcings including GHG, ozone, sulfate aerosols and solar forcing during 1900-2010; and one with prescribed observed evolution of SSTs within the tropical eastern Pacific during 1900-2010 and a slab ocean model elsewhere. These three sets of simulations will allow for attribution of sources of observed 20th-century climate variability and change.

(P2) Before the start of the proposed allocation, we expect to complete many of the CMIP5-defined simulations with fully coupled CESM1(CAM5CN) at 1° resolution, including 20th-century single-forcing simulations with only natural forcings and with only GHG forcings. This proposal includes three ensemble members each of 20th-century single-forcing experiments for ozone, aerosols, solar, black carbon, volcanoes, and land. In addition to 20th-century single-forcing experiments, we propose future single-forcing experiments based on RCP 8.5, three ensemble members each for GHGs, ozone, and aerosols. To investigate the effects of hurricanes on ocean circulation, we propose a series of 100-year runs of CCSM4 at 1° resolution. We propose two runs each applying hurricane forcings to eight individual and combined ocean basins, one run with winds only and one with winds and precipitation.

(P3) To investigate decadal predictability of the climate system, we propose a series of ten-year simulations of fully coupled CESM1(CAM5CN) at 1° resolution and prescribed aerosols with initial conditions from data assimilation. Following the new CMIP5 guidance, we propose five ensemble members starting at each year from 1961 to 2005. Because these simulations are also of interest to other WGs (for example, OMWG), we will be splitting the cost of these simulations with each working group requesting resources for 5 ensemble members per start date. We further propose to extend the ensembles for 9 of the start years by twenty years each. For future production experiments in decadal prediction, we expect to benefit from the development work sponsored by the SDWG.

Experiment	Model Configuration	# runs	# of years	Core hour / year	Total in core-hours	Total data volume in TB	Priority
P1. Fully coupled control	B, CESM1(CAM5CN) 1°	1	1500	910	1365000	40	A
P1. Atmosphere control	F, CAMCN 1°	1	1000	720	720000	12	A
P1. Slab-ocean control	E, CESM1(CAM5CN-SOM) 1°	1	1000	800	800000	15	B
P1. 20th C SST forcings + regional slab-ocean	B, CESM1(CAM5CN) 1°	3	150	910	409500	12	A
P2. RCP single forcings	B, CESM1(CAM5CN) 1°	9	100	910	819000	24	A
P2. RCP modified forcings	B, CESM1(CAM5CN) 1°	6	100	910	546000	16	B
P2. 20th C modified forcings	B, CESM1(CAM5CN) 1°	15	150	910	2047500	59	C
P1. 20th C SST + Radiative forcings	F, CAM5CN 1°	20	150	720	2160000	37	A
P1. 20th C SST forcings	F, CAM5CN 1°	10	150	720	1080000	19	B
P3. Decadal prediction	B, CESM1(CAM5*CN) 1°	180	10	500	900000	48	A
P3. Decadal prediction	B, CESM1(CAM5*CN) 1°	36	20	500	360000	19	A
P3. Decadal prediction	B, CESM1(CAM5*CN) 1°	45	10	500	225000	12	C
P3. Decadal prediction	B, CESM1(CAM5*CN) 1°	9	20	500	90000	5	C
P2. Hurricane effects	B, CCSM4 1°	16	100	300	480000	32	A
TOTAL					**12.002M**	**350**	

Land Ice Working Group

Research Plan and Overview of Objectives

The primary objectives of the Land Ice Working Group (LIWG) are (1) to couple a well-validated, fully dynamical ice sheet model to CESM, and (2) to determine the likely range of decade-to-century-scale sea-level rise associated with the loss of land ice. These goals were partly achieved with the release of CESM 1.0, the first publicly available IPCC-class climate model with a dynamic ice sheet model. During 2012-2014, CSL resources will further advance these goals by enabling ongoing development and application of the Community Ice Sheet Model (CISM), both in standalone simulations and coupled to CESM. The improved versions of CISM and CESM will be used for high-fidelity, high-resolution scientific experiments that will significantly advance our ability to estimate future ice mass loss and sea-level rise.

In order to provide improved sea-level projections, ice sheet models require efficient, scalable dynamical cores ("dycores") with realistic physics parameterizations. Glimmer-CISM, the ice sheet model in CESM 1.0, is a serial code with simple "shallow-ice" dynamics. During the past several years, LIWG members have been developing parallel, "higher-order" dycores that can resolve fast flow in ice streams and ice shelves, as required to simulate ongoing changes in the Greenland and Antarctic ice sheets. With CSL support, we will implement these improved dycores in future versions of CISM and CESM, starting with the release of CESM 1.1 later in 2012.

Also, we are extending the coupling between ice sheets and other climate components. CESM 1.0 includes one-way coupling between the ice sheet and land/atmosphere components. The surface mass balance (SMB) of ice sheets is computed by the land model, CLM, in multiple elevation classes and is then downscaled to the dynamic ice sheet model. We have obtained excellent results for Greenland's present-day SMB. We are now implementing two-way coupling between CISM and CLM, which will allow CLM's topography and land surface types (i.e., glacier or vegetated) to change as ice sheets advance and retreat. This feedback is needed for proposed century-to-millennial-scale simulations with large changes in ice thickness and extent.

Meanwhile, we are implementing ice-sheet/ocean coupling, as required to simulate the evolution of marine ice sheets such as the West Antarctic Ice Sheet. In addition to ice-sheet model development, we are beginning to model smaller glaciers and ice caps, whose contribution to near-term sea-level rise is expected to be comparable to that of the two large ice sheets. Taken together, these efforts will give CESM the ability to simulate all the major contributions to ice mass loss and associated sea-level rise.

Development Objectives

The LIWG has the following major near-term development goals:

1. Develop and test scalable, higher-order dynamical cores for CISM

   These dycores have been developed with support from the DOE Ice Sheet Initiative for Climate Extremes (ISICLES) and will be further developed (pending review) under a new DOE project, Predicting Ice Sheet and Climate Evolution at Extreme Scales (PISCEES). The new dycores have higher-order velocity solvers that can simulate fast flow in ice streams and ice shelves, improving on the existing shallow-ice approximation. These dycores also solve prognostic equations for the evolution of the ice thickness and 3D temperature fields. The three dycores under development are:

   - The SEACISM (Scalable, Efficient, and Accurate Community Ice Sheet Model) dycore, which uses finite-difference methods on a regular grid and has recently been parallelized and linked to Trilinos software libraries;
   - The Berkeley ISICLES (BISICLES) dycore, which uses finite-volume methods based on the Chombo adaptive-mesh-refinement software package;
   - The Finite Elements for Land Ice Experiments (FELIX) dycore, which uses finite-element methods and Trilinos solvers on an unstructured mesh, and will be implemented in the Model for Prediction Across Scales (MPAS) framework. Initially, the finite-element approach will be limited to the velocity solver, with MPAS finite-volume methods used for thickness and temperature evolution.

2. Develop efficient methods for spinning up ice sheets

   We will explore new methods for bringing CISM into steady state with the CESM climate while optimizing agreement with ice-sheet observations. These methods will reduce computational costs (since we will not have to spin up the models for tens of thousands of simulation years) and minimize transient associated with ice-sheet adjustment to the CESM climate.

3. Quantify various sources of model uncertainty
   Model results can be sensitive to poorly constrained boundary conditions and ice physics parameters. Uncertainty quantification (UQ) is required to estimate upper and lower bounds that are of interest to planners and policy makers.

4. Validate and refine the surface-mass-balance scheme in CLM
   We have already applied the new glacier SMB scheme to Greenland's surface mass balance, obtaining good agreement with observations and regional models. However, CLM's treatment of the bare-ice albedo is fairly crude, and we plan to implement a more realistic scheme. We will next apply and validate the SMB scheme for the Antarctic ice sheet (where increased precipitation in the interior and increased melting at the margins could be important as the climate warms) and to smaller glaciers and ice caps. New applications will require improved ice physics and downscaling methods.

5. Implement in CLM a dynamic landunit scheme
   This allows CLM topography and surface types to evolve in tandem with ice sheet thickness and extent. This will enable long-term 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, e.g. during the last (Eemian) interglacial.

6. Couple CISM to the POP ocean model
   POP is being modified to simulate circulation and heat exchange beneath floating ice shelves in Antarctica. This coupling is needed to simulate ice-sheet / ocean interactions that are critical for the evolution of marine ice sheets.

7. Develop models for the evolution of smaller glaciers and ice caps (GIC)
   These models will be forced by CLM surface mass balance and will use area-volume scaling relationships in lieu of full dynamics (which would be impractical for hundreds of thousands of GIC).

Goals (1) **–** (4) will be supported directly by this proposal, through simulations that allow us to improve scalability, identify biases, explore sensitivities to uncertain parameters, and test physics improvements. Goal (5) involves significant coding and software engineering, but only modest computing resources. Goal (6) is being pursued under the IMPACTS (Investigation of the Magnitudes and Probabilities of Abrupt Climate Transitions) project on abrupt climate change, and goal (7) is part of a new Regional Arctic System Model (RASM) project. The IMPACTS and RASM work will be carried out with separate DOE computing resources.

Production Objectives

The main goal of near-term production experiments is to simulate the evolution of the Greenland ice sheet under various climate scenarios, including preindustrial, present-day, 21st century, long-term (22nd century and beyond), and paleoclimate. We will also carry out some standalone Antarctic ice sheet simulations, but coupled Antarctic experiments are not yet production-ready. On a longer time scale (2 to 5 years), we plan to carry out coupled ice-sheet / ocean simulations with a dynamic Antarctic ice sheet, in order to assess the response of marine ice sheets to climate change. We will also extend the Greenland simulations to include ice-sheet / ocean interactions that will influence the evolution of large outlet glaciers.

With CESM1.0, we have already run CMIP5 simulations from 1850 through the 21st century. These simulations have used shallow-ice Glimmer-CISM with a dynamic Greenland ice sheet, with one-way coupling between the ice sheet model and the land model (CLM) and atmosphere model (CAM4). Future experiments will build on this foundation by using higher-order CISM with two-way coupling to CLM, to evaluate feedbacks on land topography and surface types. For these experiments we will use the CAM5 atmosphere model, which includes water isotopes and improved Arctic cloud physics, among other enhancements. These simulations will use standard CMIP5 scenarios (preindustrial, 20^{th} century, and RCP8.5) and will contribute to future climate assessments (beyond IPCC AR5). These will likely be the first climate simulations with a higher-order ice sheet model coupled interactively to a complex global Earth system model.

Also, we plan to simulate the long-term stability of the Greenland ice sheet under a range of climate stabilization scenarios. These simulations will identify CO_2 thresholds beyond which the ice sheet could have a negative surface mass balance and melt inexorably. For these simulations we will use higher-order CISM, since stability thresholds may depend on the rate at which the ice sheet dynamics respond to changes in climate forcing. In order to simulate many centuries of climate evolution with available computing resources, we will run the ice sheet model asynchronously, with ~10 ice-sheet years per AOGCM year.

In collaboration with the Paleoclimate Working Group, we will carry out simulations focused on the last (Eemian) interglacial. At the peak of the interglacial, global sea level was several meters higher than today, and the Greenland ice sheet was roughly half its current size. Using asynchronous coupling, we will carry out a transient simulation of the period from 130 ka and 110 ka, during which the ice sheet retreated and advanced under changing orbital parameters. We also plan to simulate the inception of large Northern Hemisphere ice sheets at the end of the last interglacial, around 115 ka.

Finally, we would like to better understand the sensitivity of ice sheet to uncertainties in future climate forcings, based on archived CMIP5 climate runs. Once we have a tuned, stable configuration for each ice sheet, we will perturb the ice-sheet forcing based on CMIP5 model output. The range of responses will give us a better understanding of likely effects of 21^{st} century climate change on ice sheets.

Proposed experiments and computational requirements

Development experiments

D1. <u>Higher-order dynamical cores for CISM</u>

We request computing resources for ongoing development, testing, and validation of CISM's three current and planned dycores: SEACISM, BISICLES, and FELIX. All dycores will require computing resources for work in the following areas. We have shown in parentheses the estimated fraction of development time for each area.

- *Testing new physical process modules (15%)*
  Ongoing code development will involve improved representation of physical processes such as iceberg calving and sub-glacial hydrology. We will implement new models of basal sliding, with more robust and efficient solution methods for complex basal boundary conditions. These parameterizations will initially be implemented in serial versions of the code, but will need to be tested for performance in parallel and at scale.
- *Performance tuning and scaling tests (15%)*
  For each dycore, many short runs will be needed for performance tuning (such as optimization of linear and nonlinear solver settings). We will test for strong scaling of all dycores by running a large problem (i.e., with high spatial resolution) on an increasing number of processors.

- *Verification and validation (20%)*
  A formal verification and validation (V&V) toolbox is planned for development under PISCEES. Computer time will be required to implement and test the V&V toolbox on all CISM dycores.
- *Optimization of initial conditions (25%)*
  A primary thrust for CISM will be the development, code integrations, and application of formal optimization methods for use in generating optimal ice sheet initial conditions. We aim to spin up the models to near-present-day conditions without running the full dycores for tens of thousands of years. For example, temperature can be spun up while holding the geometry fixed. Basal parameters can be tuned to minimize the model misfit with the observed surface velocity field and its divergence. Development and testing of these methods for the Greenland and Antarctic ice sheets will require computer time for each dycore.
- *Robustness (25%)*
  Each dycore will be tested for robustness by applying it to high-resolution, large-scale standalone simulations (e.g., Greenland and Antarctica at spatial resolutions of 5km or less) under a range of boundary and initial conditions.

For the table below, we assume a cost of 200 core-hours per simulation year for each dycore. This corresponds roughly to the current cost of running the SEACISM dycore with a 3D higher-order solver for the Greenland ice sheet at a uniform resolution of 5 km, or the cost of running BISICLES with a vertically integrated higher-order solver for the Greenland and Antarctic ice sheets combined with adaptive resolution of ~1-5 km. We estimate data storage requirements of 1.0 GB/yr for Greenland simulations and 4.0 GB/yr for Antarctic simulations. In the table, however, we have halved these storage estimates, given that much of the data generated in development runs will not require long-term archiving.

These are standard configurations likely to be used for production experiments. Costs and storage requirements will vary, however, depending on the model configuration and on ongoing improvements in scalability. For example, we will test higher-resolution configurations that could later be used in production if the models scale well enough. We are currently targeting SEACISM and FELIX mainly for Greenland experiments, but these dycores will be applied to Antarctica as they mature.

D2. <u>Improved models of ice albedo and surface fluxes</u>

We will use CSL allocations to develop a more comprehensive representation of energy fluxes at the ice-sheet/atmosphere interface, enabling more realistic simulation of ice sheet evolution and feedbacks. We will work within the current model structure, where ice-atmosphere energy fluxes are prognosed in CLM. Although CLM includes a sophisticated terrestrial snow model, originally designed for seasonal snowpack, ice sheets have a variety of unique surfaces that are not well characterized in CLM. Albedo, in particular, has a surprising degree of spatial, temporal, and spectral variability (Boggild et al. 2010).

We will develop new glacier column physics that represents variability in surface albedo associated with snow melt and exposure of bare ice, water-saturated surface snow, ponded ice, and impurity-laden surfaces in the ablation zone. This implementation will include physically-based snow, ice, and water radiation treatments (Flanner et al. 2007; Gardner and Sharp 2010; Briegleb and Light 2007), rather than prescribed constant bare-ice albedo as currently assumed in CLM. We will account for near-surface impurity accumulation in the ablation zone with an implicit scheme based on liquid water content, temperature, and altitude. The implementation process will be iterative, involving (1) comparison of model-derived surface albedo with MODIS retrievals over Greenland, (2) radiation parameter tuning, and (3) evaluation of equilibrium ice-sheet velocity fields. We will use daily-mean and instantaneous model output for comparison with MODIS, with instantaneous output timed to coincide with daily satellite overpass times. After evaluating the new surface scheme, we will conduct two century-scale coupled CESM simulations to evaluate the influence of our parameterization on simulated ice-sheet evolution, sea-level rise, and albedo feedback during the 21st century.

Experiment	Model Configuration	# runs	# of years	Core hour / year	Total core-hours	Total data volume in TB	Priority
Higher-order dycore: SEACISM	Greenland, 5 km	Many	6500	200	1300 K	3.3	AB
Higher-order dycore: BISICLES	Greenland/Antarctica, 1-5 km	Many	10,000	200	2000 K	25.0	A
Higher-order dycore: FELIX	Greenland, 5 km	Many	10,000	200	2000 K	5.0	A
Improved models of albedo and surface fluxes	IG (1^o)	~10	800	10	8 K	1.0	A
	BG_CAM5 (1^o)	2	200	910	182 K	5.3	B
Total					**5.490M**	**39.6**	

Production experiments

Many production experiments will be run with a fully coupled model including dynamic ice sheets (i.e., the BG configuration), at a resolution of 0.9^ox1.25^o for the atmosphere and ~1^o for the ocean. For glacier inception we will use the FG configuration, with POP replaced by a data ocean. Other, less expensive configurations are available for model validation and sensitivity studies: in particular, the IG configuration (active land and ice-sheet models, with a data atmosphere), and the new TG configuration (active ice-sheet model, with the surface mass balance provided by a data land model). Proposed experiments are detailed below.

P1. CMIP5 suite with CISM and CAM5

We will carry out a suite of CMIP5 experiments, including a preindustrial spin-up (~150 years), a 20th century simulation (1850-2000), and a climate change simulation (RCP8.5, 200 years), using the BG configuration with a dynamic Greenland ice sheet. We have already performed similar experiments using the CAM4 atmosphere model. For the new experiments we will use CAM5, which has improved physics parameterization for the Arctic and elsewhere. We will evaluate Greenland's surface mass balance (SMB) and compare to the previous results using CAM4. For these simulations we will use the shallow-ice version of CISM with one-way CLM/CISM coupling. By archiving coupler output, we will later be able to apply the surface mass balance from these simulations to higher-order CISM dycores using the less expensive TG configuration.

P2. CMIP5 suite with two-way CISM/CLM coupling

We will carry out two additional 500-year CMIP5 suites (preindustrial, 20th century, and RCP8.5) with two-way coupling between CLM and CISM, first using the shallow-ice CISM dycore and then using a higher-order dycore. Until now, CLM has computed the surface mass balance used to force the dynamic ice sheet model, but the land topography and surface types have remained fixed. We are now implementing dynamic landunits in CLM, which will allow transitions between glacier and vegetated landunits as ice sheets advance and retreat. CLM topography will evolve dynamically over Greenland, so that the land and ice-sheet models have consistent representations of ice-sheet extent and surface elevation in a given region. We will evaluate the strength of temperature-elevation and ice-albedo feedbacks on decade-to-century time scales, and we will determine the effect of these feedbacks on the steady-state configuration of the Greenland ice sheet. These experiments will be done using the BG configuration with CAM5.

P3. <u>Evaluating the long-term stability of the Greenland ice sheet</u>
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 loss accelerated by ice-albedo and temperature-elevation feedbacks and by dynamic ice-sheet responses (e.g., faster sliding triggered by basal lubrication). To explore stability thresholds for Greenland, we will carry out several multi-century simulations with elevated greenhouse forcing. The starting point will be the RCP8.5 simulation, which will be run through 2200 under experiment (2) above. We will prescribe three multi-century CO_2 scenarios, ranging from stabilization at an elevated level to gradual reduction to near-present-day levels. The ice sheet model will be run for ~1000 years in each scenario, with asynchronous coupling (~5 ice sheet years per ocean/atmosphere year) to reduce costs. Since dynamic ice-sheet feedbacks are important for long-term stability, we will use a higher-order CISM dycore with two-way CLM/CISM coupling. We will use the CAM5 atmosphere, provided that experiment (1) shows improved results compared to CAM4.

P4. <u>PMIP3 Last Interglacial transient simulation: 130 to 110 kyrs ago (ka)</u>
Data from paleo-shorelines and fossil corals indicate that global sea level during the Last Interglacial (LIG) was +4 to +6 meters relative to present. Rates of sea-level rise associated with Greenland ice sheet melting, as well as the timing of the sea-level signal, are still debated. Annual mean land and ocean surface temperatures are estimated to be approximately 2°C warmer than preindustrial climate, with questions on the time sychroneity of the records and uncertainties associated with seasonality of biological proxies. We propose to run a long transient simulation for the LIG and into the glacial inception that ended the LIG, using CESM(CAM5) at 1° resolution with a dynamic Greenland ice sheet. Previous work by the LIWG (pre-industrial, 20^{th}, and 21^{st} centuries) has shown that the 1° resolution gives a much better simulation of Greenland ablation than does 2° resolution. Orbital forcing of the LIG can be calculated from precise astronomical equations, and the evolution of greenhouse gases has been reconstructed from Antarctic ice cores. The results will also be useful for forcing offline models of the West Antarctic Ice Sheet being developed by the community. To realistically complete a 20,000-year transient simulation, we will accelerate the orbital forcing by a factor of ten, thus allowing the AOGCM simulation to be 2000 years in length. This orbital acceleration factor has been shown to give reasonable results in previous tests with CCSM as well as other climate models, as long as the deep ocean was not changing too much. Geological data suggests that this is a reasonable assumption. We plan to use the shallow-ice version of CISM, which should yield an adequate response on millennial time scales. (We will consider using a higher-order version, however, if it is available when the simulation begins.) This simulation is a joint project with the Paleoclimate WG, with each WG asking for 50% of the total computing time and data volume.

P5. <u>Inception of Northern Hemisphere ice sheets</u>
In addition to the full transient LIG simulations, we propose two CAM5-CISM simulations of Northern Hemisphere glacial inception around 115 ka. These simulations are a joint project with the Paleoclimate WG. A reasonable time scale to build ice sheets is 10,000 years. To accomplish this, we will use an asynchronous scheme with a coupling ratio of 1/10 (i.e., 1,000 CAM5 years at 1° and

10,000 CISM years at 5-km resolution). The shallow-ice version of CISM will be coupled dynamically to CLM, so that land topography and surface types can evolve as glaciers advance. CISM will be run on a recently developed grid that includes middle and high latitudes of the Northern Hemisphere, allowing for inception of Laurentide and Siberian ice sheets. Previous studies suggest that higher frequency of climate-ice sheet coupling leads to higher ice volumes that improves the comparison to geological estimates (though still an underestimate). Our second CAM5-CISM simulation will explore the sensitivity to the coupling interval. These coupled simulations will complement the Paleoclimate Working Group's high-resolution CAM5-SOM simulation, allowing a better understanding of the relative importance of accumulation, ablation, and ice dynamics in ice-sheet formation.

P6. Evaluating ice-sheet response to uncertainties in climate forcing

Even if uncertainties associated with ice-sheet dynamics can be reduced, large uncertainties associated with future climate forcings will remain. To quantify these uncertainties, we will evaluate the sensitivity of ice-sheet responses to perturbed forcings, which will be derived by scalings from existing archived CMIP5 simulations. In particular, we will use archived RCP8.5 model runs to examine the range of likely responses to climate forcing of ice sheets. Until recently, these runs would have been prohibitively expensive. However, the newly-developed BISICLES dycore (which has been coupled to CISM) uses adaptive mesh refinement (AMR) and parallel scalability to make such an ensemble of runs feasible. These runs will primarily use the IG configuration; archived climate output will provide forcings for CLM, which will generate a surface mass balance that is downscaled to CISM. Initially we will focus on Greenland's SMB, and later we will simulate the response of both ice sheets to ocean warming using ice-shelf melt parameterizations based on ocean temperature and salinity. We plan to run ~15 CMIP5 models for 350 years each (1850-2200), for a total of ~5000 simulation years.

The following table summarizes the proposed production experiments. An asterisk denotes experiments shared with the Paleoclimate Working Group; the number of years, core-hours, and TB of data storage shown in the table represent 50% of the total to represent the LIWG contribution to the experiment. The core-hour and data storage estimates are based on benchmarks for standard configurations (including B, F, and I at 1^o resolution), combined with our best estimates of CISM costs. We assume a cost of ~200 cpu-hours per simulation year for a higher-order ice sheet model. The cost of the shallow-ice dycore is negligible. For CISM data storage, we assume a requirement of 1.0 GB/yr for Greenland, 4.0 GB/yr for Antarctica, and 4.0 GB/yr for Northern Hemisphere paleo ice sheets.

xperiment	**Model Configuration**	**# runs**	**# of years**	**Core hour / year**	**Total core-hours**	**Total data volume in TB**	**Priority**
P1. CMIP5 suite with CAM5	BG_CAM5, CISM_SIA	1	500	910	455 K	13.7	A
P2. CMIP5 suite with two-way CLM/CISM coupling	BG_CAM5, CISM_SIA BG_CAM5, CISM_HO	1 1	500 500	910 1110	455 K 555K	13.7 13.7	A A
P3. Long-term Greenland stability	BG_CAM5, CISM_HO	3	600 CESM, 3000 CISM	910 CESM, 200 CISM	1150 K	18.8	AB

P4. Transient Eemian simulation*	BG_CAM5, CISM_SIA	1	1000 CESM, 10,000 CISM	910	910 K	36.4	A
P5. Ice sheet inception*	FG_CAM5, CISM_SIA	1	600 CESM, 6000 CISM	720	432 K	39.8	BC
P6. Ice-sheet response to climate uncertainties	IG, CISM_HO	~15	5000	210	1050 K	31.0	BC
Total					**5.000 M**	**167.1**	

Land Model Working Group

Research Plan and Broad Overview of Objectives

The goals of the Land Model Working Group are 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 possible to separate land biogeophysics development from land biogeochemistry development. For this allocation request, land biogeochemistry model development has been included in the Land Model Working Group request. A portion of the proposed terrestrial carbon cycle production work has been included in the Biogeochemistry Working Group request.

Development Objectives

The Community Land Model 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, which will culminate in a release of a new version of CLM (CLM4.5) during the CSL allocation period. Many of the model development projects from the last CSL proposal are ongoing. Over the past several years, CLM4 has undergone detailed scrutiny by a broad range of model users and developers, in the process identifying several aspects in which the model can be improved. Many of the biases that have been identified appear to be related to interactions between model biogeophysical and biogeochemical processes. Through collaborative efforts across the Land Model Working Group and the Biogeochemistry Working Groups, the biogeophysical model development and biogeochemical model development is now being completed in a more integrated fashion. Several members of the LMWG and BGCWGs are involved in an international project that aims to advance the development of a land models through a benchmarking effort in which the biogeophysical and biogeochemical performance of the model can be evaluated in a systematic and coordinated fashion.

The other major model development thrust involves expansion of the capabilities of the model. Improving the suitability of the model for high resolution simulations is one such thrust. This involves gathering and processing high resolution surface input datasets (e.g., soil texture, vegetation types, glacier, lake, and urban fractions) and enabling a high resolution version of the River Transport Model. Efforts are also underway to incorporate additional as yet unrepresented aspects of the land system including methane emissions, prognostic wetland distribution, and ecosystem demography. 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 either prescribed or prognostic 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 LMWG focuses on the use of CESM to improve the understanding land processes and their feedbacks to the rest of the earth’s climate system. Model developments for CLM4 and model developments in preparation 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 significant portion of the allocation will be used to participate in a series of international model intercomparison projects that are designed to study land-atmosphere interactions, land cover change, the terrestrial hydrological cycle, and the permafrost-carbon and other carbon cycle feedbacks.

Proposed Experiments and Computational Requirements

Development Experiments

In the table below, we lump the requested resources for model development into several classes of integrations that would be completed during a typical model development cycle. For pure biogeophysical aspects, CLM4SP (SP stands for prescribed Satellite vegetation Phenology) will typically be run for 50 years from 1960-2010. 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, the group at LBNL have developed methods that speed up the spinup process by more than a factor of two, which means that the spinup of the carbon and nitrogen states, when required, is less than 1000 years (it was 2000 years or more for CLM4CN). We have requested time for several CLM4.5CN spinup simulations. Finally, we include a request for time to do several decadal-scale CAM5/CLM4CN simulations to test and evaluate the impact of the new parameterizations on land-atmosphere interactions. For the first half of the allocation period, an intensive phase of model development is anticipated as we strive to build CLM4.5 (which mainly involves final incorporation and an evaluation of the interactions of several completed or nearly completed model development projects and parameter sensitivity/estimation studies). In parallel and especially after CLM4.5 is built, we will move on to several additional model development activities. Additionally, we note that implicitly embedded within our request for allocations devoted to model development are resources that we will provide to external model development collaborators. Past experience suggests that collaborators come to us with useful model development projects that were not included in the original CSL proposal but that are best tested and integrated on NCAR computer systems and we plan to accommodate reasonable requests for computation time under the LMWG allocation. The primary model development activities that we anticipate over the length CSL allocation period are outlined briefly below. Several smaller projects are not explicitly listed.

Vegetation processes

Multi-layer canopy: Land surface models treat the plant canopy as a single "big leaf," or in the case of CLM as two big leaves that represent the sunlit and shaded fractions of the canopy. Considerable theoretical and observational studies show that the big-leaf approach fails to fully capture the non-linearity of radiative transfer with depth in the canopy and within-canopy gradients of leaf traits, temperature, humidity, etc. Multi-layer canopy models do represent these gradients and will be implemented and tested in CLM.

GPP parameter sensitivity: Prototype multi-layer radiative transfer has been implemented in CLM, with the result that (i) leaf physiological traits used in the model are consistent with observational databases of leaf traits and (ii) gross primary production (GPP) simulated by the model is also consistent with observational estimates. Parameter sensitivity studies will quantify uncertainty related to the range of possible leaf trait parameter values that provide acceptable GPP.

Leaf trait coordination: Major differences in leaf age, leaf nitrogen content, and maximum leaf photosynthetic rates are found among various plant functional types (e.g., evergreen and deciduous, needleleaf and broadleaf). Observational studies find a globally universal coordination among these three leaf traits. Parameter sensitivity studies will test this theory in CLM.

Ecosystem Demography

The Ecosystem Demography (ED) 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 determined by 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. The ED model has been implemented in CLM and is operational at regional scales. A full global deployment is expected in the lifetime of the CSL allocation. The new CLM(ED) model will require computer resources for spin-up runs and for parameter sensitivity experiments. ED requires multi-level gas exchange calculations, and therefore represents an approximately 3-fold increase in cost over the CLM4(CN) model. The majority of work on exploring the model sensitivity to an ensemble of parameter inputs at low spatial resolution. These runs will be subjected to benchmarking data, and those that achieved the highest benchmarking standards will be spun up at high resolution and used for transient simulations.

Urban Model

The urban model will be expanded to include multiple urban landunits, multiple urban landunits, improved anthropogenic flux parameterizations, suburban model with integrated vegetation and irrigation, and variable layers for roofs and walls.

Crop Model

Crop-model development will focus on the corn, cereals, and soybean working with CLM4CN's interactive nitrogen cycle using a prognostic fertilization scheme. The crop types will be expanded to include tropical crops.

Soil parameterization

Current representation of soils in the CLM are relatively simplistic with only one (dominant) soil type represented in each grid cell, and all grid cells held to a fixed soil depth. However, it is well known that soil depth and soil properties can influence local climate conditions and vegetation productivity. Hence we hypothesize that creating more realistic soil depth and soil properties, and linking these to appropriate vegetation types will improve our surface climate simulation especially in wet and dry climate regions.

We will conduct a number of experiments to incorporate soil more realistically and to evaluate the potential feedbacks associated with these improved parameter settings.

Model-data fusion / data assimilation

NEON and other ecological observatories (ICOS, LTER, FLUXNET) provide data that can be utilized for continental-scale ecological forecasting, but new statistical and analytical tools are required that are capable of synthesizing them. We are developing a model-data fusion framework in which a variety of remote sensing and ground based ecosystem measurements made across a range of temporal and spatial scales can be combined with the Community Land Model (CLM) to produce optimal solutions for model parameter values, states and fluxes. This framework will enable spatial extrapolation of observations and ecological forecasting. A multi-instance version of CESM has been developed that more easily facilitates ensemble-based model-data fusion techniques, and which has now been coupled to the Data Assimilation Research Testbed.

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 and to enable the capability to run CLM with the DGVM at the same time as prescribed land cover change.

Experiment	**Model Configuration**	**# runs**	**# of years**	**Core hour / year**	**Total in thousand core-hours**	**Total data volume in TB**	**Priority**
CLM4SP Development Expts	I, CLM4 (1°)	100	50	10	50	6	A
CLM4CN Development Experiments	I, CLM4CN (1°)	100	110	10	110	12	A
CLM4CN Spinup	I, CLM4CN, I, CLM4.5CN (1°)	20	1000	10	200	6[1]	A
CLM4.5 Parameter Sensitivity/Estimation	I, CLM4CN (2°)	2000	100	3	600	8[1]	B
CAM5/CLM4.5 Testing	I, CAM5/CLM4.5 (1°)	50	50	720	1800	31	A
CLM(ED) Testing	I, CLM4(ED) (1°)	20	1000	30	600	24	A
CLM(ED) Parameter Sensitivity	I, CLM4(ED) (2°)	2000	100	10	1000	8[1]	B
Data assimilation/NEON	I, CLM4CN (1°) I, CLM4CN (0.5°) I, CLM4CN (point)	64 64 128	50 50 100000	15 (est) 80 (est) 0.01	48 256 128	1[1] 4[1] neg	A C A
Total					4792	100	

[1] Data volume estimates are reduced by a factor of 4 for spinup, parameter sensitivity, and assimilation experiments as archival of most variables is not required for these experiments

Production Experiments

Land Model Intercomparison Projects

There are several land model intercomparison projects that are in development. These projects include:

- TRENDY – an Intercomparison project that focuses on reconstructions of land carbon fluxes associated with historical land cover/land use change, climate, and CO_2 fertilization
- GSWP3 - focuses on the water cycle and water-carbon interactions over the 20th century
- Vulnerability of Permafrost Carbon Research Coordination Network – Historic assessment and future projections of carbon dioxide and methane emissions to the atmosphere due to permafrost thaw
- LUCID – CAM/CLM simulations for the LUCID model intercomparison project on the biogeophysical impacts of land cover change will be repeated with fully coupled time-slice simulations for 1850 and 2000 boundary conditions for CAM5-CLM4 and CAM5-CLM4.5 model configurations
- GLACE-CMIP5 – CAM/CLM simulations forced with SST from fully coupled simulations with soil moisture climatology prescribed to assess the feedbacks of projected changes in soil moisture on climate and extremes. The protocols for several of these model intercomparisons are not fully defined yet, but for the land only intercomparison projects we are budgeting for 6 simulations of 125-year duration at 0.5° resolution for each project

Land cover change

The CCSM4 CMIP5 climate modeling experiments represented the impacts of historical and projected human land use on the climate system and the carbon cycle through time series of cropping, pastural grazing and wood harvest (Lawrence et al. 2012). The land use representation for each of these time series was prescribed from historical reconstructions, and from IAM future scenarios generated for each of the RCPs. To isolate and assess uncertainties in the terrestrial carbon cycle response due to land cover change trajectories, we propose to repeat several CCSM4 RCP experiments with the land cover change trajectories from different RCPs swapped in. We will focus on the two extreme land cover change scenarios of RCP 4.5 (reforestation) and RCP 8.5 (wood exploitation). Additional historic simulations without land cover change will also be conducted.

A second set of experiments will investigate the impact of scale on the simulated climate feedbacks due to land cover change. At low resolution, the real land cover change is smoothed out. We propose to conduct a set of experiments using the new regionally refined capability of CESM to investigate how the land cover change response varies for finely or coarsely scaled land cover change and finely or coarsely scaled atmosphere.

Urban heat stress and urban-climate interactions

Conduct uncoupled high resolution CLM urban (CLMU) simulations over the U.S. partly in support of the SIMMER (System for Integrated Modeling of Metropolitan Extreme Heat Risk). 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. A set of uncoupled high resolution (1/8°) simulations over the U.S./Southern Canada will be performed with atmospheric forcing determined from downscaled present-day WRF/Noah simulations forced with AR5 20th century CCSM4 simulations. One of the foci will be to assess the potential of various strategies for mitigating urban heat island effects. High temporal resolution output is a requirement for several of these runs. Additionally, several high resolution CAM/CLM simulations will be completed to assess the impact of urban areas, which is fairly minimal at low resolution, in high resolution CAM simulations. Finally, we will conduct several future urban time slice experiments at 0.5° that will permit an investigation into the impact of anticipated 21st century urbanization.

Impact of crops and crop management on carbon cycle

Offline and online experiments will be conducted with the updated version of the CLM4 crop model, including prognostic fertilization. We will assess the effect of crops on the carbon cycle using the fully coupled CESM.

Experiment	Model Configuration	# runs	# of years	Core hour / year	Total in thousand core-hours	Total data volume in TB	Priority
MIPs Offline (TRENDY, GSWP3, Perm-Carb) MIPs Spinup	I, CLM4, CLM4.5 (0.5°)	20 10	125 1000	60 60	150 600	11 11	A
MIPs Coupled (LUCID, GLACE-CMIP5)	B, CESM1(CAM5,CLM4/CLM4.5) (1°) F, CAM4/CLM4 (1°)	24 8	30 150	910 190	655 228	13 5	B A
Land cover change expts	B, CCSM4 (1°)	12	125	300	450	30	B
Land cover change – scale investigation	B, CESM1(CAM5/CLM4.5) (ne30, ne120))	6 2	30 30	1000 5600	180 336	4 2	A
Urban heat stress	I, CLM4CN (1/8° U.S.)	36	960	90	86	9	A
Urban-climate	F, CAM5-SE (ne60) F, CAM5-SE (ne120)	4 2	30 10	10000 50000	1200 1000	18	A C
Crop-carbon	I, CLM4.5 (0.5°) B, CESM1(CAM5, 1°)	10 5	100 50	60 910	60 227	5	A B
Total					**4592**	**108**	

References

Lawrence, P. J., and Coauthors, 2012: Simulating the Biogeochemical and Biogeophysical Impacts of Transient Land Cover Change and Wood Harvest in the Community Climate System Model (CCSM4) from 1850 to 2100. *Journal of Climate,* in press.

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Ocean Model Working Group

Research Plan and Broad Science Objectives

The primary goals of the OMWG are to i) 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 ii) conduct curiosity driven research with CESM to advance our understanding of the role of the oceans in the Earth's climate system.

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 generations of the CESM simulations. We are requesting computational resources to address the following ambitious development goals:

- Improving physical and numerical representation of processes that include true freshwater fluxes, vertical coordinate, vertical resolution, and model time stepping
- Improving subgrid scale parameterizations
- Investigating the topographic control of the Gulf Stream / North Atlantic Current to directly address associated temperature and salinity biases,
- Developing an eddy resolving ocean model that includes many of the recent physics improvements of the standard ocean model such as submesoscale mixing and anisotropic mesoscale parameterizations
- Pursuing nested and new modeling approaches

The OMWG has established a path forward to consider the Model for Prediction Across Scales Ocean component (MPAS-O) for use in the next plus one version of CESM. Although this effort will require order five years to reach full maturity, it is anticipated that some preliminary simulations will be performed with MPAS-O to test functionality and to highlight some of its capabilities during the lifetime of this proposal. Meanwhile, we are committed to improve and maintain our current model (Parallel Ocean Program version 2, POP2) as the ocean model for the next CESM version. Towards this goal, we decided on a path to address some long-standing algorithmic shortcomings of POP2 in our December 2011 OMWG meeting. Accordingly, we will i) implement the so-called z* vertical coordinate to address the possibility of thin (in comparison to free surface displacements) uppermost layers, ii) eliminate the virtual salt fluxes (and associated treatment for other tracers such as Carbon) in favor of true freshwater surface fluxes, and iii) modify the time stepping scheme to introduce a conservative Robert filter to facilitate high frequency coupling, i.e., order 1 hour. All of these developments are highly needed for many science applications, e.g., given intense interest in sea level rise and incorporation of a land-ice component in the CESM framework, abandoning the virtual salt flux approach to represent the exchange of freshwater between the ocean and other model components is an urgent model development for POP2, and more frequent coupling of the ocean – than the current once-a-day coupling – allows for resolution of diurnal cycle and inertial periods.

We plan to allocate a significant fraction of our resources to the development of our eddy-resolving model as we anticipate more usage of this version with our increased computational capabilities. Specifically, we will upgrade the physics packages used in our earlier high resolution simulations, e.g., include submesoscale mixing, tidal mixing, etc. Moreover, we will increase the number of vertical levels from 40 to 60, as in our current coarse resolution version.

In addition, we will continue to investigate the causes of ocean model biases and to develop new, and improve upon, extant subgrid scale parameterizations. These will strongly leverage the efforts of the university community, including projects funded by the National Science Foundation (NSF) Earth System Model (EaSM) and Climate Process Team (CPT), and the Department of Energy (DOE) Scientific Discovery through Advanced Computing (SciDAC) programs. For all these development efforts, the broad science objective is to understand the behavior of physical processes, 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 (BGCWG) members to assess the impacts of these new developments on the ocean ventilation and biogeochemistry, e.g., oxygen minimum zones and carbon uptake.

Finally, some of our activities involve other ocean models within the CESM framework. We view these as an important element of our development work because they help in investigation of model biases and deficiencies.

Production Objectives

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

- Evaluation of new parameterizations and assessing their climate impacts
- Investigating the impacts of model parameterizations on climate variability, particularly on the variability of the Atlantic Meridional Overturning Circulation (AMOC)
- Performing data-assimilation-initialized decadal prediction simulations and supporting CESM's participation in the National Multi-Model Ensemble project
- Performing an eddy-resolving ocean – sea-ice coupled simulation
- Contributing to the integration of a long, pre-industrial control simulation that uses CAM5

The OMWG 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. We have completed our implementations and testing of some newly developed parameterizations. It is now time to assess their climate impacts as this is an important objective of both CPTs.

AMOC is thought to play an important role in decadal and longer time scale climate variability as well as in prediction of the Earth's future climate on these time scales. Through its associated heat and salt (freshwater) transports, AMOC significantly influences the climate of the North Atlantic and surrounding areas. Changes in surface temperatures linked to AMOC variability can impact global climate through atmospheric interactions on interannual to multi-decadal to even centennial time scales. As our recent investigations revealed significant influence of some model subgrid scale parameterizations on AMOC variability, we are proposing a set of experiments to document sensitivity of AMOC variability to a few parameter choices related to meso and submesoscale mixing. In addition, in collaboration with the Climate Variability and Change Working Group (CVCWG), we request time to perform data-assimilation-initialized decadal prediction simulations, following the modified CMIP5 protocol.

Finally, we plan to allocate a modest fraction of our resources to i) an eddy-resolving ocean – sea-ice simulation to document its solutions in comparison with an identically forced nominal 1^o resolution case and ii) a coupled control experiment that uses CAM5 with prognostic aerosols to study its intrinsic oceanic and sea-ice variability. The former experiment will use a version of our eddy-resolving model, including new developments in subgrid scale closures as described below. The latter is in collaboration with both the Polar Climate Working Group (PCWG) and Climate Variability and Change Working Group (CVCWG).

Proposed Experiments, Science, and Computational Requirements

Unless otherwise stated, all simulations use the nominal 1^o horizontal resolution versions of all component models. In the following descriptions, we use the CESM component set terminology. Consequently, the ocean – sea-ice coupled simulations are referred to as G cases and the fully-coupled integrations are called B cases. Most of the G cases will be forced with the Coordinated Ocean-ice Reference Experiments (CORE) inter-annually (IAF) varying atmospheric data sets, covering the 1948-2007 period. Hence, a 120-year simulation, for example, cycles this forcing data twice. Unless otherwise noted, B cases use CAM4. Finally, our intent is to make use of existing simulations as our control cases in most of the proposed experiments.

Model Developments

D1. POP2 numerical and algorithmic developments

We will i) implement the z* vertical coordinate, ii) eliminate the virtual salt fluxes and associated treatment for other tracers such as Carbon, and iii) modify the time stepping scheme by introducing a conservative Robert filter in POP2. There are nontrivial issues associated with all these developments, including details of river runoff and ice fluxes with a true surface freshwater flux formulation. These developments will be led primarily by OMWG members at the Los Alamos National Laboratory. As the developments are completed and passed on to NCAR, we will perform additional testing and sensitivity experiments. Here, we request resources for these integrations. Given the broad scope of these implementations, we anticipate at least order 100 G-case simulations forced with the CORE normal-year (NYF) atmospheric forcing data sets. These are expected to be order 10-year simulations. We will then conduct about ten 120-year CORE IAF simulations with about 2 of them extended to 300 years. The final step is to document the impacts of these new developments in 500-year long fully coupled simulations. We anticipate at least two such simulations: i) with z*, freshwater fluxes, and 1 hour coupling, and ii) same as before but a longer coupling interval. We note that our estimates in the table assume the computational costs will remain the same as in the original code.

D2. Anisotropic Gent and McWilliams (GM) parameterization

Eddy resolving / permitting model simulations suggest an anisotropic form for the GM isopycnal transport parameterization instead of its commonly used isotropic form. We have just completed implementation of an anisotropic GM operator based on earlier work in POP1.4 so that it can be used in our current model version POP2. Such a formulation can have significant impacts on model simulations, particularly on ocean ventilation – its improvement is a key science goal of our working group. We believe that our new anisotropic GM implementation is now ready for exploratory sensitivity experiments. We request resources for about ten 120-year, CORE IAF G-case experiments to document sensitivity of model solutions to various prescriptions of the anisotropic diffusivity coefficients. We intend to perform two additional, 300-year G-case CORE IAF simulations with BGC to document the impacts of the parameterization on BGC. These two experiments will use our top two best choices for this closure based on the above sensitivity experiments. One of these choices will also be used in a 500-year fully coupled simulation to assess the impacts of such an anisotropic formulation on climate, variability, and ocean BGC.

D3. Langmuir mixing

Some recent diagnostic studies suggest that turbulent energy available for mixing within the ocean surface boundary layer could be grossly underestimated without forcing by surface waves. Wave-forcing, and hence Langmuir turbulence, could be important over wide areas of the ocean and in all seasons in the Southern Ocean, including during summertime when there are known biases in the boundary layer depth in the CESM ocean component. Therefore global climate models need to represent wave forcing of Langmuir turbulence in their boundary layer parameterizations, which may well require that global climate models also need to compute the surface wave field. To include these physics, we have incorporated the NOAA Wave Watch III (WWIII) wave model into CESM as a separate component. Here, we request resources to test our implementation. We anticipate conducting about five 120-year G-case CORE IAF simulations, followed by two 150-year B experiments. We estimate that the use of the WWIII model will double the per-year cost of the model.

D4. Gulf Stream and North Atlantic Current path

Arguably one of the most prominent biases in all the CESM coupled simulations is the large surface temperature and salinity errors in the northern North Atlantic Ocean, resulting from the incorrect separation of the Gulf Stream (GS) and the subsequent, too-zonal path of the North Atlantic Current

(NAC). To directly address these biases, in a collaborative EaSM project, we are investigating the topographic control of the GS with the central hypothesis that processes at the western boundary of the North Atlantic (that include lateral form stress and potential vorticity generation by lateral and bottom topography) exert the primary control on GS separation and the NAC pathway and that these processes are currently either absent or poorly represented in models. The ultimate goal of the project is to develop new parameterizations to represent these missing physics. In the meantime, we are conducting a systematic exploration of the GS separation and NAC path to some details of the bottom topography, involving details of how discrete topography is obtained from the ETOPO 1 minute data. We plan to investigate the sensitivities to various levels of raw and discrete topography smoothing, to using minimum and maximum depths instead of the mean depth to represent discrete topography, to modifying certain upstream and downstream topographic features, etc. Although we anticipate about 20 B-case experiments, because the above biases emerge quickly, order 30-year simulations will be sufficient.

D5. Modeling Ocean Variability and Biogeochemical Cycles (MOBY)

In this collaborative EaSM project, the aim is to advance understanding of coupled physical, chemical, and biological processes in the ocean that respond to and feedback on the global climate. Specifically, we attempt to understand the oceanic mesoscale and its interaction with biogeochemical cycles. The ultimate goal is to obtain new and improved mesoscale parameterizations (considering biogeochemical interactions) and assess their impacts on climate, variability as well as on decadal predictability and projections of climate change, using CESM. As part of this project, we have incorporated the MIT Darwin ecosystem model as a CESM component. We will soon start testing this model configuration, performing many short integrations. We do not have a cost estimate for this configuration yet, but expect it to be high because the Darwin model uses over 70 species. Here, we request 150000 core hours to perform these initial tests.

D6. Increased vertical resolution

Our previous (pre-CCSM4) studies showed significant bias reductions in ocean model solutions with increased vertical resolution (up to 100 levels). Our current usage of 60 vertical levels was chosen as a compromise between computational expense and improved physics. We believe that with the current increase in computational resources, it is prudent to reconsider an increase in model vertical resolution for the next version of our model. Moreover, the new z* vertical coordinate capability described above will permit a more flexible choice of near surface resolution. Our request is for order five 120-year CORE IAF G-case simulations along with one 500-year fully-coupled integration. Assuming order 100 vertical levels and a linear increase in model cost, the ocean model cost will go up by 31 core hours per simulation year.

D7. Parameterization of land-ocean freshwater exchange

At present, river runoff is treated as extra precipitation, distributed over a broad, prescribed, area of the sea surface. New parameterizations are under development with the DOE SciDAC support that will treat the exchange of freshwater through estuaries and coastal river plumes, in a more physically based way, using energetic constraints on the amount and depth of mixing between open ocean seawater and terrestrial freshwater. We will conduct 4 experiments of 120 years each using CORE IAF G-case and two 500-year B-case simulations to evaluate these parameterizations.

D8. Eddy-resolving ocean model development

The subgrid scale closure assumptions used in forced ocean and coupled integrations with the 0.1^o configuration of POP2 do not reflect recent advances in our understanding of adiabatic (submeso and mesoscale lateral mixing) and diabatic (vertical mixing) ocean physics. In the first phase of this development effort, we propose to carry out a series of experiments, exploring the sensitivity of the global ocean model forced by CORE data sets, to a switch from level-coordinate based biharmonic closure, to more adiabatic closure assumptions. In particular, we will test the near-surface submesoscale closure and the anisotropic GM closure already implemented in POP2. In the second phase, we intend to test impacts of vertical physics, e.g., tidal mixing, near-inertial waves, in the eddy resolving regime. These experiments will be carried out in a 60-level version of the model (same as the current 1^o ocean component, increased from 40 levels in previous high resolution studies). It is anticipated that with the increased cost of the more advanced parameterizations (approximately 25% over simpler closures) and increased vertical resolution (50% from previous versions) the cost will rise from a recently measured 17000 core hr/year to 32000 core hr/year. We are requesting resources for six G-case CORE NYF integrations of 15 years each, and a 50-year long fully-coupled run with our best choice set of closure assumptions based on the preliminary experiments.

D9. Regional ocean modeling studies
This research is investigating whether nested high-resolution ocean modeling can reduce the biases of sea surface temperature and salinity seen in coastal regions of global CESM simulations. The nested models are used to provide improved representation of processes such as coastal upwelling, freshwater runoff, and topographically-constrained flows. The simulations serve to both provide a direct assessment of the impact of these processes on the global climate, and to serve as a baseline against which to test parameterizations of these processes. The project will extend the implementation of the Regional Ocean Modeling System (ROMS) at a resolution of 0.1° in the North-East Pacific within the global POP2 (and hence in CESM). This work is in close collaboration with other OMWG efforts (see D11) exploring the alternative approach of local mesh refinement using MPAS-O. Here, the request is for a 300-year combination of ocean-only and ocean – sea-ice coupled simulations as well as two 150-year fully-coupled integrations. Our Yellowstone-core-hours-per-year estimates are based on existing nested regional modeling integrations on Bluefire.

D10. Marine ecosystem experiments using ROMS
This developmental research focuses on using ROMS to examine and predict the vulnerability of coral reef ecosystems in the Coral Triangle (region of maximum marine biodiversity, spanning the Philippines through Indonesia and Papua New Guinea). The goal is to determine how subtle differences in ocean circulation patterns will affect future bleaching events, as well as the likelihood that bleached reefs will reseed via transport of coral larvae from reefs upstream. A version of ROMS has been already set up in the Coral Triangle region. This model covers 25°S–30°N and 95–170°E and has a ~5 km grid that resolves the complex bathymetry of the area, including the narrow passages of the Indonesian Throughflow, which are essential for capturing the circulation, temperature, and salinity fields known to affect coral reefs. Here, we are requesting resources for one 5-year preliminary simulation in preparation for longer 20C and future scenario experiments. We estimate that one year of simulation will require about 42000 core hours.

D11. Preliminary MPAS-O experiments
We anticipate that we will begin exercising MPAS-O in ocean-only or ocean – sea-ice coupled simulations with a preliminary suite of physical parameterizations that include both the KPP vertical mixing scheme and GM parameterization. Here, we propose two 120-year ocean-only simulations forced with CORE IAF data. The first, baseline case will use an unstructured grid with a nominal 1^o horizontal resolution, but with isotropic refinement near the equator as in POP2. The second experiment will have refined mesh along all the coasts to encompass the coastal waveguides as well. This latter configuration exercises the local mesh refinement capability of MPAS-O and focuses on improvements in linear wave dynamics while avoiding any complexities associated with scale adaptive parameterizations. At this early stage, we estimate that MPAS-O will require about 110 and 165 core-hours per simulation year in respective experiments.

D12. Incorporating HYCOM in CESM

The latest version of the HYbrid Coordinate Ocean Model (HYCOM) version 2.2 was configured to run within the CCSM3 framework with the support from the DOE SciDAC and the OMWG. The performance of the coupled CCSM3/HYCOM was found to be overall comparable to the standard CCSM3/POP runs. As an extension of this work, we propose to incorporate HYCOM2.2 into the CESM framework. The main advantages of using diverse ocean models in a unique climate and Earth system model framework, i.e., CESM, lie in i) helping to reduce the structural uncertainty associated with a single ocean model and ii) enabling the reduction of model errors by the in-system comparison of numerics and parameterizations, hence aiding the further development of a new-generation ocean component in earth system modeling. The use of diverse ocean models in one single framework is not only beneficial, it is also necessary with regard to the difficulties existing in the inter-comparison of ocean models and fully-coupled models. In this proposal, we request time for order 20 fully-coupled simulations, each 10 years long, followed by two 200-year simulations. The target HYCOM horizontal resolution is the same nominal 1^{o} resolution as in POP2. There are 32 vertical hybrid depth-isopycnal layers in the current configuration of HYCOM2.2. We estimate a cost of 350 Yellowstone hours per simulation year.

Experiment	**Model Config**	**# runs**	**# years**	**Core hrs / yr**	**Total Core Hrs**	**Total data volume (TB)**	**Priority**
D1. POP2 numerical and algorithmic developments	G (NYF) G (IAF) G (IAF) B	100 8 2 2	1000 960 600 1000	56 56 56 295	56000 53760 33600 295000	15.6 15.0 9.4 19.7	A A A A
D2. Anisotropic GM	G (IAF) G (IAF, BGC) B (BGC)	10 2 1	1200 600 500	56 172 480	67200 103200 240000	18.7 27.4 23.2	A A A
D3. Langmuir mixing	G (IAF) B	5 2	600 300	2x56 2x295	67200 177000	9.4 5.9	A A
D4. GS and NAC path	B	20	600	295	177000	11.8	A
D5. MOBY					150000		B
D6. Increased vertical resolution	G (IAF) B	5 1	600 500	56+31 295+31	52200 163000	15.6 16.4	B B
D7. Land-ocean freshwater exchange	G (IAF) B	4 2	480 1000	56 295	26880 295000	7.5 19.7	B B
D8. Eddy resolving model	G (NYF) B	6 1	90 45	32000 32000	2880000 1440000	45.0 166.5	A*BC A*BC

D9. Regional modeling with ROMS	C (IAF) G (IAF) B	2 3 2	120 180 300	350 350 560	42000 63000 168000	1.9 3.1 6.0	A*BC A*BC A*BC
D10. Marine ecosystem in ROMS	C (NYF)	1	5	42000	210000	1.0	B
D11. MPAS-O	C (IAF) C (IAF, mesh refinement)	1 1	120 120	110 165	13200 19800	1.8 3.5	A A
D12. HYCOM in CESM	B B	20 2	200 400	350 350	70000 140000	3.9 7.9	C C
TOTAL					**7.003M**	**455.9**	

Production Experiments

P1. Climate Process Team on sea-ice heterogeneity and ocean mixing

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. Recently, we have implemented and tested a new parameterization that calculates vertical diffusivity and viscosity coefficients for each sea-ice category (including ice-free open ocean) within an ocean grid cell. The ocean model then uses an aggregate of these coefficients to represent the mixing for that ocean grid cell. Because this approach divides each ocean cell into multiple columns per ice categories, we refer to this parameterization as the Multi-Column Ocean Grid (MCOG) scheme. We are currently performing G-case simulations forced with CORE IAF data on our existing CSL allocation. Here, we request resources to perform half of one 1000-year fully coupled simulation that includes BGC. Because this work is joint with the PCWG, the resources for the other half are being requested in the PCWG proposal. With this simulation, we intend to explore answers to the following questions: How does MCOG work during the ice growth period? How does MCOG influence physical and biogeochemical tracers that have fluxes between ice and ocean? What are the climate impacts of MCOG? What is the importance of explicitly representing the high ice/ocean flux spatial heterogeneity in climate processes and feedbacks?

P2. Climate Process Team on internal wave driven ocean mixing

As part of our CPT activities, we have implemented a new near-inertial wave mixing (NIW) parameterization in POP2. Preliminary, short coupled simulations with this parameterization showed modest mixed layer deepening and improvements in oxygen distributions compared to a control integration without this NIW scheme. We are now in a position to assess the long-term impacts of this parameterization in coupled simulations, particularly on ocean ventilation. Of course, this has major implications on ocean CFC and BGC field distributions. Here, we propose a 500-year fully coupled simulation that includes CFCs and BGC. This simulation will also use a 2-hourly ocean coupling with the existing Leap-frog – time-averaging time stepping scheme. This is estimated to increase the per simulation year cost by about 50 Yellowstone core hours.

Another scientific application of the NIW parameterization concerns the hypothesis that the NIW mixing will lead to a positive feedback in the Arctic Ocean because newly unfrozen regions will be exposed to stronger mixing which will bring up the warm Atlantic water and further increase melting. To test this positive feedback hypothesis, we propose to perform 155-year long 20th Century simulations. For robustness of the results, we believe we need at least a three-member ensemble.

P3. Atlantic Meridional Overturning Circulation (AMOC) variability

As in many other coupled climate simulations, the CCSM4 1300-year pre-industrial control simulation also exhibits rich AMOC variability. However, in contrast with CCSM3 that had a multi-decadal variability with a 21-year peak, the AMOC in CCSM4 shows a broad spectrum of low frequency variability, covering the 50-200 year range. Recent analysis of this variability indicated that the AMOC variability mechanism, involving variability in the Labrador Sea deep-water formation location, strongly depends on the model's subgrid scale parameterizations. Here, we request resources to investigate changes in AMOC variability and mechanisms associated with some parameter changes in the ocean model. Because our study indicated important contributions from the mesoscale and submesoscale parameterizations in the Labrador Sea region, we will target the isopycnal and thickness diffusivity coefficient values, including their specified minimums, and the horizontal length scale used in the submesoscale parameterization. The latter directly impacts the strength of the submesoscale mixing. Thus, we plan to perform four 1000-year simulations branching from year 863 of the CCSM4 pre-industrial control. Such long integrations are absolutely necessary for robustness of our findings given the expected multi-decadal to centennial AMOC variability.

P4. Data assimilation initialized decadal prediction simulations

As part of our decadal prediction work, we have been utilizing ocean data assimilation via DART (Data Assimilation Research Testbed) to obtain ocean initial conditions for decadal prediction simulations. This work has been in collaboration with the DART group in CISL. Our aim is to produce a fully coupled data assimilation product for the 1960-2011 period for which we will request resources separately from the NCAR project allocations. Here, we request resources to perform the subsequent assimilation-initialized decadal prediction simulations with CESM (with CAM5 and prescribed aerosols), following the modified CMIP5 protocol. This modified protocol now calls for 10-year coupled simulations starting yearly between 1961-2005. In addition, we will increase the number of the requested 30-year simulations from 3 to 9, so that we will have additional start dates available for bias correction of these 30-year experiments. In summary, we will conduct 9 30-year simulations (starting in 1965, 1970, ….2005, i.e., every five years) and 36 10-year simulations for the other start dates. Preliminary analysis indicates that 8 to 10 ensemble members are needed for each start date for robustness. Because these simulations are also of interest to the CVCWG, we will be splitting the cost of these simulations with the OMWG and CVCWG requesting resources for 3 and 5 ensemble members per start date, respectively. We would like to also request 200000 hours to investigate sensitivity of the ocean data assimilation results to some data assimilation parameter choices such as vertical localization and representativeness error for observations. For future production experiments in decadal prediction, we expect to benefit from the development work sponsored by the SDWG.

P5. National Multi-Model Ensemble (NMME) Project

In order to support CESM's participation in the NMME, we request resources to perform seasonal hindcast experiments initialized every month from January 1980 through December 2010, each simulation running for 1 year. This is a collaborative project with the Atmospheric Model Working Group (AMWG) and here we request resources to complete 1 ensemble member for each start date. The ocean initial conditions will be obtained from the above assimilation product.

P6. Eddy resolving model forced with CORE IAF data

We propose to exercise a version of the eddy resolving ocean model (developed in D8) coupled to 0.1^o sea-ice model. This G-case configuration will be forced with the CORE IAF data and it will be the first such ocean – sea-ice coupled simulation conducted by the OMWG. We plan to integrate for 60 years. Because this simulation is of interest to both the OMWG and PCWGs, the request from the OMWG is a 40-year segment with the remaining request included in the PCWG proposal.

P7. CESM-CAM5 pre-industrial control

Multi-century long control integrations are needed to statistically characterize the multi-decadal to centennial timescale internal variability in climate models. Understanding such intrinsic climate variability is of critical importance for climate change detection and attribution studies. With its long time scale memory, the ocean is thought to play a major role in driving these low frequency signals in the climate system (as in AMOC). Although the CESM with the CAM5 finite-volume atmospheric dynamical core (with prognostic aerosols) will be used in several studies, including the *community proposal* to perform 30+ member ensemble integrations for the 1950 to 2100 period using all historical forcings and the RCP8.5 future scenario, there is no long control simulation with this configuration to assess its intrinsic variability beyond a 300-year integration. Here, we propose to extend this simulation for an additional 2000 years in collaboration with the CVCWG and PCWG as such variability is of major interest to all three working groups. The OMWG and CVCWG will request resources for 500- and 1500-year simulations while the PCWG will perform a 300-year long instantaneous CO_2 doubling experiment.

P8. Comparison of CORE inter-annually forced POP2 and HYCOM2

Both POP2 and HYCOM2 have been actively involved in a series of CORE experiments. These experiments, with a common forcing, are intended to provide a baseline experimental protocol for an ocean model intercomparison project. Indeed, the results from the first phase of this international project, involving participation from 6-7 ocean modeling groups, are already published. The second phase of this project is now underway. In contrast with the first phase that uses the NYF data, the second stage uses the CORE IAF data. Here, we propose running HYCOM2 within the CESM framework forced with CORE IAF and compare the results with those obtained with POP2. Moreover, we propose to investigate the relative role of the variabilities in different forcing fields in driving the ocean circulation and its long-term variability in both HYCOM2 and POP2. We plan to construct a series of idealized forcings that retain the mean climate of the CORE IAF data itself while isolating the main modes of the forcing at inter-seasonal, interannual, and synoptic time scales. The main modes of the forcing to be isolated include the surface forcing responding to the Northern and Southern Annular Modes, in which the high-frequency synoptic signals associated with the modes will be retained. Finally, in the comparison of HYCOM2 and POP2 by using CORE NYF, the sloshing of water masses was found in HYCOM2 – this phenomenon has also been seen in other layered ocean models. We are going to further investigate why the sloshing is occurring in HYCOM but not in POP. In summary, we plan to perform seven 300-year experiments: one control case, two HYCOM2 and two POP2 idealized forcing cases, and two simulations to investigate sloshing.

Experiment	Model Config	# runs	# years	Core hrs / yr	Total Core Hrs	Total data volume (TB)	Priority
P1. CPT – sea-ice	B (BGC)	1	500	480	240000	23.2	A
P2. CPT – internal wave mixing	B (BGC) B (20C)	1 3	500 465	480 + 50 295	265000 137175	23.2 9.2	A A
P3. AMOC variability	B	4	4000	295	1180000	78.8	A
P4. Decadal prediction	POP-DART B(20C,CAM5) B(20C,CAM5)	 3 x 36 3 x 9	 1080 810	 500 500	200000 540000 405000	 28.5 21.4	A A*BC A*BC
P5. NMME	B (20C)	372	372	295	109740	7.3	B
P6. CORE IAF in eddy resolving model	G (IAF)	1	40	32000	1280000	20.0	A*BC
P7. CESM – CAM5 pre-industrial control	B (CAM5)	1	500	908	454000	13.2	B
P8. POP2 vs. HYCOM2	G (IAF)	7	2100	56	117600	32.8	B
TOTAL					**4.929M**	**257.6**	

Paleoclimate Working Group

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.

A goal of the Paleoclimate Working Group is to provide the community with configurations of the CESM suitable for application to a wide range of paleoclimate research problems. Tasks include the ability to simulate the inception and demise of ice sheets, simulate the carbon cycle on glacial-interglacial time scales, and evaluate the uncertainties and importance of paleogeography, topography and ocean gateways for 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 and geotracers into the CESM.

The working group also carries out control experiments as part of national and international intercomparison projects. The output from these simulations is provided to the greater community and archived in the CMIP5, PMIP3, and/or ESG databases for climate change assessment and research purposes. Output from control simulations are also used to drive regional climate models and component models as starting points for further sensitivity experiments.

Development Objectives

The development objectives focus on testing and exploring a new version of CESM that will include water and carbon isotopes. Water isotopes are being used to understand the modern-day hydrologic cycle and our ability to model cloud processes correctly. For past climates, water isotopic signatures in ice cores and caves have been interpreted to represent changes in temperature, precipitation, and atmospheric circulation and in ocean sediments the changes in meltwater input. Considerable debate still surrounds these interpretations. Direct modeling within CESM and other climate models can contribute to resolution of these debates. The carbon isotopes ^{13}C and ^{14}C are used to understand the redistribution of fossil fuel carbon in the Earth System, to distinguish different carbon sources in atmospheric data, to trace oceanic water masses, to quantify ventilation time scales of the thermocline and the deep ocean and air-sea gas exchange rates, to quantify overturning rates of soil carbon and peat, and to address changes in the water use efficiency of plants and evapotranspiration under anthropogenic CO_2 forcing. Carbon isotopes as measured in ice cores and ocean sediments provide information on past water mass distribution and ventilation and on the functioning of the marine biological cycle, and provide constraints on changes in terrestrial and oceanic carbon cycle processes and their role in regulating past atmospheric CO_2. The Paleoclimate Working Group development activities will provide deeper insight and expanded capabilities in modeling paleoclimates in the CESM. We expect that these development efforts will also be useful for other working groups, e.g. the Atmosphere Model, Biogeochemistry, and Land Ice Working Groups.

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

- Implement the isotopic tracers of water into the ocean, atmosphere, and land components of CESM(CAM5) and compare to the signatures of these isotopes recorded in instrumental measurements and paleoclimate records preserved in ice cores, ocean sediments, and caves
- Determine the response of these isotopes to idealized freshwater inputs into the North Atlantic and Southern Oceans for two different climate states: LGM and modern
- Explore the sensitivity of the simulation of water isotopes to resolution of CAM5.
- Expand CESM to include the carbon isotopes ^{13}C and ^{14}C as tracers in the ocean, land, and atmosphere components of CESM(CAM5), compare simulated carbon isotopes to the extensive data for the LGM and modern, and evaluate its interpretation as a tracer representing water mass properties.

Production Objectives

The production objectives focus on the application of the CESM to fundamental questions in basic paleoclimate science. Several Model Intercomparison Projects (MIPs) have established protocols for simulating past climates. These MIPs allow for exploration of the structural differences among models. They also contain a component that emphasizes explorations of the uncertainties associated with forcings and boundary conditions. The topics that will be investigated by the Paleoclimate Working Group involve the ability of new versions and components of CESM to simulate glacial carbon cycle levels with CESM-BGC; to simulate glacial inception and Pliocene warmth with CESM-CAM5 and its better representation of Arctic clouds; to explore polar warmth and ice sheet instability with CESM-CAM5-CISM; and to revisit the role of the Tibetan Plateau, and its uplift over the late Cenozoic, on both near-field and far-field climates.

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

- Participate in an international intercomparison project (PCMIP) to evaluate and understand the capabilities of CESM-BGC to simulate the observed level of atmospheric CO_2 during past epochs
- Contribute to an international intercomparison project (PlioMIP) to understand the mid-Pliocene warm period
- Participate in the PMIP3 subproject to explore the Last Interglacial and subsequent glacial inception using both snapshot and transient simulations
- Revisit with current coupled climate models the influence of the Tibetan Plateau on global climate

Proposed Experiments and Computational Requirements

Development Experiments

Testing of coupling of water isotopes in CESM

Members of the Paleoclimate Working Group are currently implementing the isotopic tracers of water into the CESM ocean model (E. Brady and J. Zhang), CAM5 (D. Noone, J. Nussberger, C. Bardeen, and A. Gettelman), and CLM4 (D. Noone, T. Wong, and W. Riley) The necessary changes to the structure of the CESM coupler have also been started by M. Vertenstein (CESM CSEG) to allow coupling of the isotope-enabled component models. We expect the implementations and testing in the individual component models to be completed in summer 2012.

We propose a set of simulations to evaluate the coupled CESM(CAM5) with water isotopes. We propose to use the 1.9x2.5_gx1v6 version of CESM(CAM5) for the coupled experiments. This version produces a good simulation of modern climate and a long control simulation without isotopes will be completed. In addition to being less costly as compared to the 0.9x1.25_gx1v6 resolution, the increased simulated years per wall clock day makes long simulations more feasible. We propose the following set of coupled water-isotope simulations:

- An 1850 control simulation for comparison to observations. This simulation will be initialized from the non-isotope control simulation (done outside of WG) and run for 500 years.
- A LGM control simulation for comparison to proxy records. This simulation will be initialized from the 1300-year CCSM4 LGM simulation and run for 1000 years. Although the CCSM4 LGM simulation uses the same ocean model, coupling to a different version of CAM could impact the ocean circulation. We thus propose a 1000-year simulation at LGM using the CESM with water isotopes.
- Four 500-year simulations with idealized meltwater inputs will also be completed. These simulations will add freshwater in the North Atlantic and Southern Ocean starting from the completed 1850 and LGM water-isotope-enabled control simulations. The simulations with the LGM base state can be evaluated against the numerous proxy records for abrupt transitions during the last deglaciation. The simulations with the 1850 base state will be of interest to the LIWG and CVCWG for evaluating climate changes to projected melting of the Greenland and Antarctic ice sheets under future atmospheric and oceanic warming.

In addition, we propose to undertake simulations with the CAM5 model to evaluate the importance of resolution on the simulation of water isotopes in the atmosphere. These simulations will encompass a range of resolutions from the 2-degree that will be used in our coupled simulations to the 0.25-degree FV resolution of CAM5 to elucidate important processes and model errors. For example: orographic precipitation in the atmosphere improves dramatically at higher spatial resolution, so simulating isotopes in land based ice core records (Himalaya, Andes, Greenland) may improve at higher atmospheric resolutions.

Implementing and testing of coupling of carbon isotopes in CESM

Work is progressing on implementing the carbon isotopes ^{13}C and ^{14}C into the individual CESM component models of CESM(CAM5). The University of Bern research group (PaleoWG co-chair F. Joos and graduate student) is currently expanding the land component to include the carbon isotopes. Work will start on the implementation in the CESM ocean component model in May 2012 guided by the previous implementation in POP1 by N. Gruber. We will also include the two carbon isotopes as tracers in the atmospheric transport scheme of CESM and couple the carbon isotope fluxes between atmosphere, ocean, and land. These experiments will be done in the respective nominal 1-degree versions of these component models. The BGC Working Group computing request includes experiments to implement and spinup the carbon isotopes separately into the ocean model. The Paleoclimate Working Group is asking for the computer time for the land and coupled carbon-isotope experiments.

We propose the following set of carbon-isotope simulations:

- A series of short test simulations, totaling 300 years to implement and test carbon isotopes in the atmosphere and land component models.
- A 500-year simulation of the land component with prescribed atmospheric boundary conditions to run the isotopes on land into equilibrium. Isotopic values in various pools will be estimated after a few decades to speed-up the approach to equilibrium.
- A 300-year preindustrial simulation with the CESM(CAM5)-BGC with prescribed atmospheric carbon isotopes. Radiocarbon production by cosmic rays is diagnosed based (i) on the total radiocarbon inventory in the model and its lifetime of 8267 years, and (ii) on the net air-to-sea and net air-to-land fluxes and the atmospheric inventory.
- A 500-year preindustrial simulation of the CESM(CAM5)-BGC with carbon isotopes allowed to freely evolve in the ocean, land, and atmopshere models, starting from the previously spin-up under preindustrial conditions and now with the atmosphere $\delta^{13}C$ transported by the atmospheric transport scheme.
- A 1100-year coupled CESM(CAM5)-BGC with carbon isotopes under LGM climate forcing starting from the preindustrial coupled run for carbon isotopes and the PCMIP LGM simulation for physical and biogeochemical variables. New ice core data show that at the LGM atmospheric $\delta^{13}C$ - was similar to preindustrial.

The LGM and preindustrial simulations can be compared to the extensive paleo data for the LGM and satellite, aircraft and station data for modern and will allow evaluation of its interpretation as a tracer representing water mass properties.

Experiment	Model Configuration	# runs	# of years	Core hour / year	Total core-hours	Total data volume in TB	Priority
Water isotope testing[1]	B, CESM(CAM5)-water isotopes-2deg	8	3500	340	1,190,000	64	A
	F, CAM5-water isotopes: resolutions						
	2deg	1	540	200	108,000	0.4	A
	1deg	1	540	900	45,000	1.6	A
	0.5deg	1	540	3900	195,000	6.4	A
	0.25deg	1	540	26,000	1,300,000	25.6	C
Carbon isotope testing[2]	I, CLM - 1 deg	6+	800	10	8000[2]	2	AB
	B, CESM(CAM5) - BGC-carbon isotopes-1deg	3+	1900	1500	2,850,000[2]	100	AB
Total					**5.598M**	**200**	

[1] Additional cost of water isotope calculations in CESM coupled model (atmosphere, land, and ocean) is estimated to be 20% more core-hours based than standard CESM(CAM5).
[2] This carbon isotope modeling effort is joint with the BGCWG. Their computational request is covering ocean isotope experiments.

Production Experiments

Coupled Carbon-Climate in Past Epochs

There has long been an interest in the BGC and Paleoclimate Working Groups for running carbon cycle experiments in different geological epochs, e.g. LGM and 6000 year before present. This interest coordinates well with the Paleoclimate Carbon Modeling Intercomparison Project (PCMIP), an international activity that has as its purpose combining carbon cycle and paleoclimate modeling with ice-core and paleoclimate records to quantify the carbon-cycle climate feedbacks during past epochs. One 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. For each of these epochs, we are including in our request time for exploratory runs, partial spinups, and sensitivity experiments. The study of BGC in past epochs is a joint effort with the BGCWG and our allocation request combined with theirs covers all BGC in past epoch experiments. These experiments will be performed with CAM4 physics.

PlioMIP

Among the many past warm intervals, the Pliocene is of particular interest because continental configurations were very similar to modern configurations and CO_2 concentrations are reconstructed to be comparable to current values and stable. These boundary conditions provide an ideal testbed for exploring feedback mechanisms that may have contributed to the significantly warmer temperatures in the North Atlantic and Arctic, smaller polar ice sheets, and higher sea level of the Pliocene, and form the basis of the model-data intercomparison project PlioMIP. In addition to CESM, nine modeling groups are simulating the mid-Pliocene (3 million years ago) using a common experimental design for their coupled climate model experiments and for comparison and evaluation against the extensive PRISM3 project database. Two 500-year CCSM4 mid-Pliocene simulations have been completed: the standard PlioMIP experiment plus an additional simulation with the Bering Strait closed (based on some geological evidence). Both simulate a warmer Arctic and North Atlantic, with the closed Bering Strait simulation providing more warmth to the North Atlantic, but both still underestimate the proxy estimates of SST warming in this region. We will repeat these two simulations with CESM(CAM5) with its better representation of Arctic physics.

PMIP3 Last Interglacial Transient Simulation: 130 to 110 kyrs ago (ka)

Data from paleo-shorelines and fossil corals indicate that global sea level during the Last Interglacial (LIG) was +4 to +6 meters relative to present. Rates of sea level rise, associated with Greenland ice sheet melting, as well as the timing of the sea level signal, are still debated. Annual mean land and ocean surface temperature are estimated to be approximately 2°C warmer than preindustrial climate, with questions on the time synchroneity of the records and uncertainties associated with seasonality of biological proxies. We propose to run a long transient simulation for the LIG and into the glacial inception using the CESM(CAM5) at 1-degree resolution coupled to the CISM. Previous work by the LIWG (pre-industrial, 20th & 21st centuries) has shown that the 1-degree resolution gives a much better simulation of ablation in Greenland. Orbital forcing of the LIG can be calculated from precise astronomical equations and the evolution of the greenhouse gases have been reconstructed from Antarctic ice cores. The results will also be useful for forcing offline models of the West Antarctic Ice Sheet being developed by the community. To realistically complete such a long 20,000-year transient simulation, we will accelerate the orbital forcing by a factor of ten, thus allowing the simulation to be 2000 years in length. This orbital acceleration factor has been shown to give reasonable results in our previous tests with CCSM as well as other climate models, as long as the deep ocean was not changing too much. Geological data suggests that this is a reasonable assumption for the LIG and glacial inception. This simulation is a joint project with the LIWG, with each WG contributing to the total computing time and data volume.

Inception of Northern Hemisphere Ice Sheets

CCSM4 with the orbital forcing of 115 ka develops a snow cover that is consistent with what has been obtained from glacial reconstructions as the inception areas of the Laurentide and Siberian ice sheets. However, in this experiment, there is no cooling in the Southern Hemisphere, quite possibly because of the excessive westerlies. A second problem with the CCSM4 simulation is that Arctic clouds are only poorly represented, but their feedbacks could be important for the inception scenario. A third issue is that an accurate representation of orography may be important for a successful inception. The new CAM5 has significantly improved on the first two issues, and the new 0.25 degree resolution FV version has a much more highly-resolved orography. As part of the CSL effort, there will be a 200-year 1850 SOM control with the 0.25 degree CAM5. We will repeat the 115 ka inception scenario with this version. The results will allow us to assess how important Arctic clouds and orography are for ice age climate.

In addition, we propose two simulations to evaluate CAM5-CISM to simulate the glacial inception of 115 ka. These simulations are a joint project with the LIWG. A reasonable time scale to build ice sheets is 10,000 years. To accomplish this, we will employ an asynchronous scheme with a coupling ratio of 1/10, that is, 1,000 CAM5-CISM years (1 deg and 5 km resolution). The shallow-ice version of CISM will be coupled dynamically to CLM, so that land topography and surface types can evolve as glaciers advance. CISM will be run on a recently developed grid that includes middle and high latitudes of the Northern Hemisphere, allowing for inception of Laurentide and Siberian ice sheets. Previous studies suggest that higher frequency of coupling leads to higher ice volumes and improves the comparison to geological estimates (though still an underestimate). Our second CAM5-CISM simulation will explore the sensitivity to the coupling interval. These coupled simulations will complement the high-resolution CAM5-SOM simulation allowing an evaluation of the role of ice sheet-climate feedbacks and a better understanding of the relative importance of accumulation, ablation and propagation of ice in the formation of the ice sheets.

Tibetan Uplift

We propose a CESM coupled simulation to revisit the role of the Tibetan Plateau, and its uplift over the late Cenozoic, on both near-field and far-field climates. Geologically, Tibet uplift occurred in two phases: the southern margin uplift occurred first when the Indian subcontinent collided with the Asian continent, while the northern interior uplift occurred later. Physically, the initial narrow southern margin effectively formed a dynamical barrier without the large plateau-generated heating effect. Two simulations, with a modern Tibetan Plateau and no Tibetan Plateau have been completed. A third simulation is proposed to include only the southern margin uplift, thus allowing an assessment of the role of Tibet as a dynamic barrier versus elevated heat source. These simulations have implications for modeling deep-time paleo periods.

Experiment	Model Configuration	# runs	# of years	Core hour / year	Total core-hours	Total data volume in TB	Priority
Coupled Carbon-Climate for Past Epochs	B, CESM-BGC-1deg	1	3000[3]	440	1,320,000[3]	139	A
PlioMIP	B, CESM (CAM5)-2deg	2	1000	280	280,000	18	A
PMIP3-LIG Transient	B, CESM (CAM5)-CISM-1deg	1	1000[4]	910	910,000[4]	36	A
Glacial Inception	B, CESM (CAM5,SOM)-0.25deg FV	1	40	26,000	1,040,000	26	AB
	CAM5-CISM	2	1400[4]	720	1,008,000[4]	93	BC
Tibetan Uplift	B, CESM-2deg	1	1000	280	280,000	18.5	C
TOTAL					**4.838M**	**330**	

[3] The Paleoclimate and Biogeochemistry Working Groups are proposing to share these simulations. The number of years, total core-hours, and total data volume represent the Paleoclimate Working Group contribution.
[4] The Paleoclimate and Land Ice Working Groups are proposing to share these simulations. The number of years, total core-hours, and total data volume represent the Paleoclimate Working Group contribution.

Polar Climate Working Group

Research Plan and Broad Overview of Objectives

The Polar Climate Working Group (PCWG) is a consortium of scientists who are interested in understanding and modeling Arctic and Antarctic climate and its relationship to global climate. To enable polar science within the PCWG and the CESM project as a whole, we request computing resources for both polar-specific CESM parameterization development and for polar-specific CESM scientific research. To take advantage of the significant increase in projected CSL resources, we propose to use computationally demanding capabilities available within CESM including data assimilation, high-resolution simulations, and large ensembles. We anticipate both publishable and frontier results will result from the diversity of activities we propose, and that these results will provide new understanding of polar climate processes.

Development Objectives

The overarching objective of our development experiments is to ensure that CESM has state-of-the-art abilities to simulate polar climate. Specifically, we request resources to incorporate new polar-relevant physics into the sea ice model (CICE) and atmospheric model (CAM) used in CESM. CSL resources will be important both to validate the implementation of new model physics and to evaluate its impact on the coupled climate system. Our proposed atmospheric data assimilation experiments are motivated by the philosophy that it is important to evaluate CESM with new techniques. Finally, although resources are not requested here, we will be actively involved in high-resolution polar development efforts being proposed within the Ocean Model Working Group (OMWG) for ice-ocean hindcast simulations, and within the Atmosphere Model Working Group (AMWG) for Arctic regional mesh refinement using the spectral element CAM dynamical core.

Production Objectives

The overarching objective of our production experiments is to inform important and topical polar climate science research questions. Specifically, we propose experiments to understand the influence of carbon dioxide, methane, and sea ice albedo on Arctic climate change, the predictability of Arctic sea ice, and the importance of sea ice heterogeneity and ocean eddies to polar climate. Many of our proposed production experiments will be done in collaboration with other CESM working groups (OMWG, CCWG, CVCWG). Our climate sensitivity and ensemble PCWG production experiments use the same CESM configuration as the proposed ensemble community projects (CESM-CAM5 FV 0.9x1.25). Significant production resources are also requested to evaluate the polar climate processes within CESM at high horizontal resolution. Because our proposed experiments leverage project-wide production experiments and expertise, we anticipate they will have enhanced scientific value and broad appeal within the CESM project and the broader polar climate science community.

Proposed Experiments and Computational Requirements

Development Experiments

<u>D1. Improve the representation of sea ice processes within CESM</u>

During the period of performance of this proposal, the CESM and LANL versions of CICE will be unified to incorporate desirable developments that have occurred in both. The common CICE code base will be released to the public in the middle of 2013. The LANL-based CICE parameterizations that will be incorporated into CESM will improve the process representation of melt ponds, ridging, anisotropic dynamics, multi-phase physics, and biogeochemistry. We also plan to evaluate and improve the representation of surface albedo including the impact of snow aging and of precipitation events such as rain-on-snow events. Development resources are requested to test the impact of all of these new CICE parameterization developments in coupled 1850 controls and in coupled instantaneous doubled carbon dioxide experiments.

<u>D2. Evaluation and improvement of CAM physics using CAM atmospheric reanalysis and forecasts enabled by data assimilation</u>

Data assimilation (DA), an emerging tool for climate model evaluation and improvement, is a supported capability in CESM through the Data Assimilation Research Testbed (DART). DA is particularly important when leveraging short observational records and in polar regions, which have both large climate variability and a greater-than-global forced response to increased greenhouse gases. In addition, DA can be used to test the ability of new observations to improve initial value model predictability. Given these known and the still-being-discovered reasons to use DA, the PCWG proposes to collaborate with DART scientists to produce a CESM-CAM5 based atmospheric reanalysis. This reanalysis will provide atmospheric initial condition for running short-term data-initialized forecasts using CAM, a modeling strategy has proven useful for identifying CESM physics errors (e.g., Kay et al. 2011). DA with CAM may also be useful for planning of future international field experiments such as the Arctic drift station currently being discussed by the International Arctic Science Committee (IASC). We propose to produce the CESM-CAM5 based reanalysis during SHEBA field campaign (September 1997 - October 1998) and also during recent periods of extreme observed Arctic sea ice loss. Given the significant computing expense of DA and that model physical parameterizations are often similar at 1 and 2 degrees horizontal resolution, we will use a 2-degree version of CESM-CAM5 for the proposed assimilations. Precedent for using 2-degree atmosphere-only data assimilation has been set by the assimilations that have already been completed with CESM-CAM4 (1.9x2.5 FV) which are available from 1996 to 2010.

<u>D3. Evaluation and improvement of atmospheric dynamics parameterizations to improve high-latitude atmospheric circulations (joint with AMWG)</u>

The appreciable influence of unresolved and therefore parameterized atmospheric dynamics on polar atmospheric circulation patterns has been increasingly evident in CESM. For example, the Beaufort High, a feature of known importance to Arctic sea ice distributions and variability, is weaker-than-observed in CCSM4 but stronger-than-observed in CESM-CAM5, a difference that is partly traceable to their differing representation of turbulent mountain stress (TMS) within CAM. In addition, the initial coupled versions of CAM5-SE had a degraded polar wintertime climate due to the specification of smoother orography than was used in CAM5-FV. Orography is a boundary condition for CAM that is an important input to both the TMS and gravity wave parameterizations. As such, we propose to evaluate and improve the influence of orographic boundary conditions, surface stress, and gravity waves within CAM on the high-latitude climate in CESM-CAM5. Because the stratosphere has important effects on high-latitude tropospheric circulation patterns, we propose to test the influence of these atmospheric dynamics parameterizations in coupled runs with and without a fully resolved stratosphere. Parameterization modifications will be recommended to the AMWG for implementation within CESM-CAM5-SE if they improve atmospheric circulations, especially the polar atmospheric circulation patterns important for sea ice distributions.

<u>D4. Assess and improve atmospheric moist physics parameterizations for polar regions in the next-generation version CAM (joint with AMWG)</u>

Members of the AMWG are currently developing scale-aware moist physics parameterizations (UNICON, CLUBB, cloud PDF approximations) and advanced treatment cloud microphysics and aerosols for possible inclusion in the next-generation version of CAM (see AMWG P9, P10). Within this CSL request, the AMWG proposes to provide climate validation for these parameterizations (see AMWG P4). Historically, the suitability of proposed and utilized CAM moist physics for polar regions has received less attention than lower latitudes. Yet, the polar regions often have unique processes and characteristics that are important to consider when developing moist physics parameterizations. As a result, the PCWG requests resources to evaluate and improve the next generation moist physics parameterizations being developed for CAM with a specific emphasis on polar boundary layer, turbulence, clouds, and precipitation processes. Evaluation of cloud and precipitation processes with satellite observations will leverage the instrument simulator package COSP, a package implemented in CESM that has been used to evaluate polar cloud distributions within CAM4 and CAM5 (Kay et al. 2012). As such, some of the computing resources requested here will be used to perform COSP implementation, validation, and CAM evaluation work.

D5. Snow parameterization sensitivity experiments

As work utilizing PCWG CSL resources in the past year indicates, the role of snow in modulating winter ice growth is an important element in accurate simulation of ice growth. Recent results have indicated that CCSM4 produces a significant excess of snow, which inhibits ice growth. In addition, other work currently in preparation implies decreasing 21st century snow depth triggers a negative feedback to continued ice are decreases through enhanced wintertime ice growth. Due to these findings, we propose to continue characterizing the ice response to additional CICE snow parameterizations to determine the appropriate additions to future CICE versions. CICE currently makes use of a fixed snow density and conductivity. We will implement seasonally and temperature based density and conductivity parameterizations to determine the sensitivity of the ice cover. In addition, previous results have indicated the ice response to snow depth is also a function of ice thickness. We will test the model sensitivity to snow redistribution between ice thickness categories. Observations suggest ice redistributes from thin, smooth ice to thick, rough ice. We expect this parameterization will serve to enhance ice growth, and will test the sensitivity.

Experiment	Model Configuration	# runs	# of years	Core hour / year	Total in million core-hours	Total data volume in TB	Priority
D1. CICE development, full depth ocean model	CESM-CAM5 SE (ne30np4)	4	100	1,000	0.40	10.6	A
D1. CICE development, slab ocean model (SOM)	CESM-CAM5 SE (ne30np4) SOM	10	60	700	0.42	8.6	A
D2. Atmospheric reanalysis for CESM-CAM5	CESM -CAM5 FV (1.9x2.5) atmospheric data assimilation	1	3	200,000	0.60	9.0	A*BC
D3. Improve polar CAM dynamics	CESM-CAM5 SE (ne30np4)	10	30	1,000	0.30	7.9	B*C
D3. Improve polar CAM dynamics	CESM-CAM5 SE (ne30np4) with WACCM	3	30	3,500	0.32	15.8	B*C
D4. Improve polar CAM physics	AMIP CAM SE (ne30np4) with COSP	10	10	2,200	0.22	2.5	B
D4. Improve polar CAM physics	CESM-CAM SE (ne30np4) with COSP	10	10	2,800	0.28	5.3	C
D5. Snow sensitivity studies	CCSM4 FV (1.9x2.5) SOM	6	60	85	0.03	3.6	C
Total					**2.57**	**63.3**	

Production Experiments

P1. Documenting internal climate variability and the idealized response to increased greenhouse gases in CESM-CAM5 (joint with CVCWG, OMWG)

Multi-century long model runs are needed to statistically characterize internal climate variability and the climate response to external forcing. Measuring internal climate variability is critical for climate change detection and attribution studies, especially for extreme events. Although CESM-CAM5 is being used in many integrations proposed for this CSL, including community proposals to study climate over the last millennium and into the future using ensembles, the corresponding CESM-CAM5 control run is only 300 years long and no fully coupled idealized response to 2xCO_2 has been performed. As such, three working groups (PCWG, CVCWM, OMWG) are jointly proposing to study internal variability and the response to 2xCO_2 in CESM-CAM5. The PCWG contribution to this effort is a 300-year long climate sensitivity experiment. The climate sensitivity of CESM-CAM5 will be evaluated by measuring the climate response to an instantaneous doubling of 2xCO_2 concentrations branched from an 1850 control run. Recent work has suggested that slab ocean experiments can accurately quantify climate sensitivity (Danabasoglu and Gent, 2009), but continued testing of this assumption with fully coupled models is warranted. In addition, the role of deep ocean circulation in 2xCO_2 climate change can be investigated by comparing slab ocean model runs and fully coupled model runs with a dynamic deep ocean circulation.

P2. Eddy resolving model forced with CORE IAF data (joint with OMWG)

High-resolution experiments are a groundbreaking focus of this entire CESM CSL proposal. In this spirit, the PCWG and OMWG jointly propose to complete a hindcast experiment with an eddy resolving ocean model coupled to a 0.1-degree sea ice model (CICE) within the CESM framework (G-case configuration). This proposed activity is a first attempt to use high-resolution versions of the CESM ocean and ice models in a hindcast mode over the observational record. PCWG CSL resources from the previous POP were used to gain experience with 1-degree CORE forcing experiments. OMWG are proposing to determine the optimal physical parameterization settings for this run (see D8 of OMWG proposal). Assuming these activities generate an attractive model set-up, the OMWG and PCWG jointly propose to complete one 60-year cycles of 0.1-degree coupled ice and ocean hindcasts forced by the CORE-IAF atmospheric forcing during this CSL POP. The PCWG contribution will be 20 years of integration, while the OMWG contribution will be 40 years of integration.

P3. Climate Process Team on sea-ice heterogeneity and ocean mixing (joint with OMWG).

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. Recently, a CPT project has implemented and tested a new parameterization that calculates vertical diffusivity and viscosity coefficients for each sea-ice category (including ice-free open ocean) within an ocean grid cell. The ocean model then uses an aggregate of these coefficients to represent the mixing for that ocean grid cell. Because this approach divides each ocean cell into multiple columns per ice categories, we refer to this parameterization as the Multi-Column Ocean Grid (MCOG) scheme. The PCWG and OMWG jointly propose to complete a 1000-year fully coupled simulation that includes BGC to test the influence of the MCOG scheme by each contributing 500 years of model integration.

P4. Understanding climate impacts of increased 21st century methane release (joint with CCWG)

The Arctic contains vast quantities of organic carbon in frozen soils and continental shelf sediments. Release of this carbon in the form of methane fluxes to the atmosphere is recognized as a primary vulnerability in the global carbon cycle, with the potential to create large positive feedback on climate warming. While the mechanisms governing methane release are uncertain (and their representation under development), CESM does have robust representations of the processes necessary to determine the climate impact of such a release. Thus, the PCWG and the CCWG jointly propose to investigate the climate impacts of increases in atmospheric methane, driven by Arctic release during the 21st century. We will specify spatially explicit sources of methane as additional forcing, imposed mid-century during the RCP8.5 CMIP5 scenario. Methane has a lifetime of about 10 years in the atmosphere; removal occurs via conversion to carbon dioxide and water vapor. Therefore, key questions regarding the climate impacts of methane release include both the total quantity and temporal structure of fluxes to the atmosphere. We will specify an array of physically plausible, but idealized release scenarios, with the objective of understanding the sensitivity and persistence of methane-derived effects. Our analysis will be aimed at quantifying short- and long-term impacts on the climate system, including radiative effects, as well as dynamic and chemical responses in both the ocean and atmosphere.

P5. Evaluating the effect of increased sea ice albedo to mimic geoengineering on Arctic climate during 21st century

Greenhouse simulations in CCSM4 suggest that the retreat of Arctic sea ice and snow cover triggers remote atmospheric circulation changes in middle latitudes that enhance meridional flow and thus promote persistent weather patterns that favor extreme events (droughts, floods, heat waves, and cold-air outbreaks). To test this hypothesis, we propose a transient simulation driven by the RCP8.5 scenario using CESM-CAM5, in which increasing their surface albedos artificially hinders the melting of Arctic sea ice and snow cover. Comparing this "geoengineered" run with the standard CESM-CAM5 greenhouse-forced simulation will show whether the model's muted polar response with raised albedos produces more zonal circulation and less extreme weather in middle latitudes than the standard run. This experimental design allows the effects of cryospheric loss to be isolated, yet enables surface-atmosphere interactions and participation by the dynamical ocean, thus permitting realistic feedback processes. An ensemble is requested both for assessing extreme events which may be difficult to detect with a single ensemble member and also for sensitivity tests to determine the albedo increase that provides the most desirable solution.

P6. Sea ice predictability experiments

Extreme Arctic sea ice reductions have been observed in recent years. This is consistent with rapid ice loss events (RILEs) simulated by CESM. Because of considerable natural variability in the Arctic, CESM simulations also exhibit instances of increasing sea ice on decadal timescales even well into the 21st century. A better understanding of the character, impacts and potential forecasting of sea ice and extreme ice events have numerous implications for Arctic marine access. Here we seek to assess the predictability of extreme Arctic sea ice variations and their associated impacts on Arctic weather and climate. This includes a set of initialized ensemble predictability experiments to assess inherent predictability in the context of CESM and a set of experiments that are designed to investigate the factors that can contribute to a degradation of potential predictability in the real system.

More specifically, we propose four sets of 25-member ensemble simulations of 4-years length for the following cases:

- Inherent Predictability Runs: Each set will use identical ocean-ice-land initial conditions with small (round-off level) changes in the initial atmospheric state. This will allow us to assess the inherent predictability in the system. Five different initial conditions will be used to diagnose the role of different initial states on predictability characteristics. These initial states will include 1850 preindustrial control, 20th century and 21st century conditions to assess how large changes in the Arctic climate system influence seasonal-interannual predictability
- Inaccurate Initial Condition Runs: Random anomalies will be applied to initial sea ice conditions to mimic observational measurement errors. For example, the quantified uncertainties associated with satellite retrievals of sea ice thickness will be used to derive applied perturbations to initial ice thickness conditions
- Sparse Initial Condition Runs: A sparse distribution of initial ice conditions will be used - the details of which will be determined through consultation with the observational community. The "missing" data will be filled with various methods such as a correlation length scale analysis and climatological values.

- Incomplete Initial Condition Runs: An incomplete set of initial conditions will be used in which certain variables (such as ocean temperature) are replaced with climatology. Consultation with the observational community will determine the variable set used

The potential predictability in sea ice conditions realized in ensemble sets 2-4 will be compared to our "perfect" initial condition ensemble simulations (#1 above) to determine the degradation of predictive potential, what sources of initial condition errors are most critical for a loss of predictive capability, and whether the degradation in predictive potential varies for different variables, regions, and times of year. These experiments will further our understanding of the mechanisms influencing predictability of Arctic sea ice conditions and will contribute to Arctic observing network design considerations. They will also inform us as the "realizable" predictive potential given various errors in initial conditions.

P7. High-resolution Antarctic ocean circulation experiments

Dense water forms around Antarctic when surface waters cool and/or increase in salinity near ice shelves and polynyas. Deep (1000-4000 m) warming in the Southern Ocean is seen in observations of the past few decades and in simulation of the 20th and 21st centuries. The warming sequesters heat and delays warming at the surface, protecting Antarctic ice sheets. There is disagreement about the cause of the deep Southern Ocean warming in observations. We propose to study the problem with CESM. Typical coarse resolution ocean models do not resolve polynyas or the plumes of sinking dense water. Fine resolution (0.1-deg) ocean-sea ice climate models capture the polynyas and have greatly improved Southern Ocean hydrogaphy, with temperature below 2000 m about 0.5-1 deg colder than coarse resolution models in much of the Southern Ocean. Preliminary work has shown that ozone depletion and the subsequent enhancement of westerly surface winds does not cause deep warming in the Southern Ocean at fine or coarse resolution. In contrast, ramping CO2 causes deep warming in the Southern Ocean at both fine and coarse resolution. We propose to run sensitivity experiments to further understand the mechanisms, by isolating the effects of buoyancy changes from sea ice changes and ice shelf changes.

Experiment	**Model Configuration**	**# runs**	**# of years**	**Core hour / year**	**Total in million core-hours**	**Total data volume in TB**	**Priority**
P1. Climate sensitivity	CESM-CAM5 FV (0.9x1.25)	1	300	900	0.27	7.9	A
P2. Eddy resolving ice-ocean hindcast	CICE/POP (0.1 degree) with data atmosphere	1	20	32,000	.64	10.0	A
P3. CPT – sea-ice heterogeneity	CCSM4 (0.9x1.25_gx 1v6) with BGC	1	500	480	0.24	23.2	A
P4. Methane ensemble	CESM-CAM5 FV(0.9x1.25)	6	50	2,300	0.69	12.0	B
P5. Ice albedo ensemble	CESM-CAM5 FV (0.9x1.25)	6	96	900	0.52	15.2	B
P6. Sea ice predictability	CESM-CAM5 FV (0.9x1.25)	125*4	4	900	1.80	52.8	A*BC

P7. High resolution coupled studies of Antarctic ocean circulation	CESM with CICE/POP (0.1 degree), CAM5 SE (ne60np4)	1	18.5	53,000**	0.98	13.0	B*C
Total					**5.14**	**134.1**	

** This core-hour/yr value is an estimate based on similar runs on Kraken. When the actual core-hour/yr estimate is known, we will adjust the number of years to obtain the same core-hour total.

Societal Dimensions Working Group

Research Plan and Broad Overview Objective

The overall goal of the Societal Dimensions Working Group is to enhance CESM and its application in order to improve understanding of the interactions between human and earth systems. The group was started in 2011 with a focus on interactions between CESM and two research and user communities: integrated assessment modeling and water management. More broadly, the group's mission is to foster and sustain dialogue between the CESM community and other communities of researchers and practitioners studying interaction of society and climate change and variability and implementing measures to adapt to or mitigate climate change.

Although the working group has not yet had a first open meeting, prior to its formation a workshop on Societal Dimensions of Earth System Modeling was held with the participation of the wider research community to identify and prioritize key areas of focus. In a White Paper developed out of that meeting, specific areas of initial focus for the group were identified: in the area of integrated assessment modeling, interactions between human and earth systems mediated by land use, and in the area of water, a pilot project on CESM hydroclimatology to inform water management. At the same time, the topics of climate and air quality, as well as a possible cross-cutting focus on water in both IAMs and CESM, were identified as additional objectives worth exploring as future topics. In addition, it was concluded that the working group should leverage existing activities in the research community and look for key opportunities to add value. Examples included building off the RCP/CMIP5 process, linking to particular Energy Modeling Forum or water community studies, and bridging to the integrated Earth System Model (iESM) project. During this initial formation period bringing together two distinct research communities, the IAM and Water areas will be treated separately. The intent is, as time progresses and these communities mature, to better integrate the research topics as true areas of crosscutting work emerge.

The request for this working group is consistent with the focus recommended in the White Paper. In the area of integrated assessment, requests involve model runs intended to assess key scientific issues regarding land use that require linking CESM to integrated assessment models and model outputs. These include understanding the potential magnitude and significance of regional climate feedbacks on land use, improving the representation in CESM of land use activities critical to IA modeling such as agriculture, biofuel production, and forestry, and developing improved methods of linking IAMs with CESM. The approach to all of these issues will involve two components. First, activities will test the degree of coupling between CESM and IA models that is required to address particular issues, by comparing results with (1) IAMs linked to CLM without coupling to the rest of CESM, (2) one-way linkages between IAMs and CESM, and (3) full coupling, particularly through cooperation with the iESM project. Second, these activities will be carried out within the framework of the RCP/CMIP5 process, so that results will also be useful to understanding key open questions regarding the consistency between IAM analyses of RCPs and earth system model simulations based on them.

In the water focus area, there is much activity within research and user communities to incorporate more sophisticated climate modeling in integrated studies and to obtain climate change information best suited for their particular needs, i.e. best suited in terms of the temporal and spatial statistics required for their specific applications. For example, water resource managers seek information on local water availability as input to their decision making processes. This decision process involves modeling and empirical information of the hydrological cycle on multiple space and time scales. Similarly, researchers exploring the role of land use in climate change mitigation and impacts need to better understand how land use will affect climate change and how climate change may influence land use decisions. Such understanding requires exploring a variety of feedbacks between the climate system and socio-economic processes. These processes are adaptive, meaning they recognize the need to design flexibility into the management/decision process, and to evolve with climate information, and also are concerned with extremes, means and the evaluation of threshold decision points for both resource availability and demand. With the loss of "stationarity" as a uniform baseline for making resource planning and demand management decisions, water managers recognize the pressing need to bring climate data and projections into their decision management structure.

Development Objectives

IAM

Simulations related to integrated assessment modeling of the role of land use are requested to improve the representation of key land use activities important to the coupling of IAMs and CESM. The Land Model Working Group is requesting allocation for development in the area of agricultural and forest systems, as well as in ecosystem dynamics. Here we request allocation for investigating the utility of the representation of these processes in CLM for linking to integrated assessment modeling. This work will involve developing and testing algorithms for translating IA model land use outputs, which often involve different variables and classification systems, into inputs consistent with CLM.

Water

The water sector was selected as one of the initial pilot projects for the CESM societal Dimensions Working Group due to its enormous economic and societal significance and its broad multi-scale temporal and space needs ranging from continents to watersheds and centuries to minutes. In addition, this sector is very experienced in integrating a wide spectrum of scientific, economic and societal data, along with their attendant uncertainties, into their management and planning processes. The conclusions of the Societal Dimensions Working Group formation workshop were in close agreement with a recent detailed analysis by the water utility industry of the lessons-learned from using current climate model data for their climate change planning on priority areas for improvements in the climate models by

- Improving CESM hydrology by reducing model uncertainty and bias and
- Providing relevant Hydroclimate variables for downscaling and decision-making.

Where possible, proposed experiments will align with both the SDWG research aims and the recommendations in the "Options for Improving Climate Modeling to Assist Water Utility Planning for Climate Change" report put out by the Water Utility Climate Alliance.

Production Objectives

IAM

Simulations related to integrated assessment modeling of the role of land use are requested to carry out coordinated modeling and assessment in four areas: interpreting IA model land use scenarios in CESM, assessing the importance of regional climate feedbacks, assessing the importance of model coupling, and evaluating possible future activities in the area of air quality. For CMIP5, IA model land use scenarios were implemented in CESM as described in Lawrence et al., 2012. This experience identified important problems with the translation of IA model outputs regarding areas and amounts of carbon harvested from of forests over time. A set of well defined RCP-based CESM simulations using land use scenarios from three different IAMs are requested that will help define a new methodology for translating IAM land use inputs to CESM. In the area of regional feedbacks, a set of CESM simulations that test alternative patterns of land used change (generated by alternative IAMs) in three different regions. These simulations will evaluate implications for regional climate, and the model outputs will in turn be used to evaluate responses in IAMs. In addition, an allocation for iESM experiments is requested in order to assess the value of full coupling (vs. one-way coupling). iESM is an integrated system that fully couples the GCAM integrated assessment model to CESM, and iESM simulations of the same experiments will be compared to one-way experiments to develop insights into the relative value of different degrees of model coupling. Finally, in order to evaluate options for future working group activities related to air quality, an allocation is requested for testing the sensitivity of RCPs to alternative scenarios of short-lived emissions. These sensitivity analyses will inform working group discussions over the next year of a coordinated model experiment to carry out on the air quality issue.

Water

Improvements and strategies coming out of the development phase will be validated by simulating the impacts of climate change on important precipitation hydrologic systems, namely:

A. American monsoon and
B. Droughts in the American southwest

The strong emphasis on short timescales and extremes means that some practical matters will need to be addressed, such as how to save or estimate the required extreme climate variables from the climate simulations without generating data volumes too big to be usable.

Proposed Experiments and Computational Requirements

Development Experiments

1. <u>Improved RCP-based land use and land cover change representation in CESM and IAMs</u>

For all of the NCAR CMIP5 climate modeling experiments the impacts of historical and projected human land use on the climate system and the carbon cycle in CESM were represented through new time series of cropping, pastural grazing and wood harvest as described in (Lawrence et al. 2012). The land use representation for each of these time series was prescribed from historical reconstructions, and from IAM future scenarios generated for each of the Representative Concentration Pathways (RCPs). While the land use trajectories in CESM captured the general intention of the land use generated in the historical reconstructions and IAM models, there is still a large amount of human activity and climate impact science not currently represented in CESM. To improve this situation, coordinated modeling work between IAMs and CESM must be carried out that will likely involve modifications to both types of models in order to improve the ability to assess key scientific issues regarding land use.

Following the Societal Dimensions Working Group 2011 white paper, it was agreed effort should be placed into developing consistent CESM and IAM representations of the three human managed areas of: (a) agricultural systems (including pastoral activity); (b) secondary and disturbed forestry systems; and (c) biofuel production and management. Representing various elements of each of these human activities in CESM is a current priority for the Land Model Working Group. We intend to extend the scientific developments currently being brought into CLM in order to ensure that they are best matched to outputs and approaches to modeling land use in IAMs. More specifically:

A. Agricultural systems: Improving the representation of agricultural systems in CLM follows the work of (Levis et al. 2012), which includes simulating multiple crop types, with a range of management regimes. This work is being further extended to include application of fertilizer, crop nitrogen fixation, and crop yield simulation. Future work may also include representing grazing by herbivores on pasture.
B. Secondary and disturbed forestry systems: The inclusion of the Ecosystem Demography (ED) model (Moorcroft et al. 2001) in CLM is an ongoing project with an implementation described in (Fisher et al. 2010). The representation of secondary forest and successional forest development is an important improvement in the representation of land use and land cover change in CLM with the carbon cycle able to represent vegetation at various stages of recovery from human disturbance. This is a key element that was not represented the CMIP5 experiments but prescribed explicitly in the harmonized land cover change time series provided by (Hurtt et al. 2011).
C. Biofuel production and management: Many of the IAM land use trajectories included representations of biofuel production through either cropping or wood harvest. The improvements in representing agricultural systems, and in secondary and disturbed forestry systems will allow biofuels to be explicitly included in CLM. The additional features in terms of crop yields and managed forest harvest will allow the assessment of the effectiveness, cost and climate impacts of biofuel production in CESM in comparison to current representation in IAMs. This work will require CESM simulations as well as simulations not requiring full coupling between CLM and the rest of the model (i.e., configuration ICN,(0.47x0.63)).

2. <u>Improving CESM Hydroclimatology to inform water management</u>

A priority area for working group is to understand and quantify the uncertainty and bias associated with the water processes in represented in the CESM, and providing hydroclimate variables that are relevant for water management studies. This will involve generation of large model ensemble sets both understand the sources of uncertainty and to increase confidence in the ranges of GCM projections, comparing the CESM hydrology with existing models to evaluate biases in key variables (bias in context) and working to improve simulations of critical regions such as the tropical Pacific and short-term decadal prediction. The group could also explore the issue that watershed hydrologic models using downscaled climate variables may give hydrology (fluxes, states) inconsistent with the underlying climate model. Candidate model groups: NARCCAP data, CAM AMIP and CCSM with different scales, BCSD in collaboration with industry members of the working group, both through San Francisco Public Utility and the Water Utility Climate Alliance and its activities. In this initial year, most of the SDWG runs will be coordinated with similar runs carried out by other working groups that already have been allocated the human resources needed to carry out the simulations.

A. Improving CESM hydrology by reducing model uncertainty and bias

Characterizing and managing uncertainty and model bias in the CESM precipitation and land hydrology will be required for the climate model products to be integrated into the decision process. The four priority areas are aligned with the recommendations outlined in the WUCA “Options for Improving Climate Modeling to Assist Water Utility Planning for Climate Change” (OICM) report.

2A1. Development and enhancement of global climate model ensembles

The water utility industry is requesting a significant increase in number ensemble members for climate simulations in order to increase the confidence in the range of model predictions, particularly over the next 50 years. The CESM Large Ensemble community project addresses this request and the SDWG will support five of the additional complimentary members of the 1950-2099 simulations

2A2. Improved use of observations to constrain climate model projections.
The OICM assessment recommended developing and applying methods to use observations of past climate and the emerging climate change signal to narrow the range of climate model projections. In the absence of a proven climate data assimilation capability, the SDWG will participate in the Last Millennium Community Project through the support of two additional complimentary 1000+ year paleoclimate simulations.

2A3. Improved modeling of the Tropical Pacific
This area is beyond the scope of the current SDWG capabilities and will require coordination with both the atmosphere model and ocean model working groups in this area over the next year. Accordingly no work resources are requested for this topic until a suitable development strategy can be defined.

2A4. Improved decadal prediction
The CMIP5 represented the start of a global coordinated effort to achieve decadal prediction as part of the climate modeling capability. Climate Variability and Change Working Group (CVCWG) and the Ocean Model Working Group (OMWG) are collaborating on a series of production experiments for decadal prediction that will also benefit SDWG. To enable further improvements to decadal prediction, SDWG proposes follow-on development experiments, a series of six experiments of ten ensemble members each.

B. Providing relevant Hydroclimate variables for downscaling and decision-making

Water management models such as watershed hydrologic models using downscaled climate variables may give hydrology (fluxes, states) inconsistent with the underlying climate model. Seamless data integration over this multi-scale/multi-time continuum would need to be resolved.

2B1. The OICM report issued 3 concrete recommendations for improvement in this area: Development of regional climate change ensembles - Regional climate model simulations, Development of RCM model components and Development of statistical downscaling techniques for probabilistic downscaling, extremes, and daily data. The actual implementation of this will require carrying out regional climate model simulations for a control period, historical simulation and future projections, then improving the components and statistical downscaling approaches. The target SDWG allocation for this allows for 15 years of 1/4° CESM simulations as part of the high-resolution community project. This element will be refined at the SDWG group meeting February.

Experiment	Model Configuration	# runs	# of years	Core hour / year	Total core-hours	Total data volume in TB	Priority
1A Land use and land cover change representation	B_1850_CN (0.9x1.25_gx1v6)	36	100	300	1080000	72	A
1B	ICN (0.47x0.63)	36	100	60	216000	15	A
2A1 Ensembles	B, CESM-CAM5 1°	5	150	910	825000	23	ABC
2A2 Obs/Paleo	B, CESM-CAM5 2°	2	1155	280	646800	43	B
2A3 TropPac							
2A4 Decadal	B, CESM-CAM4 1°	60	10	500	300000	19	C
2B1 Regional	CESM .25°	1	500	56000	840000	46	A
TOTAL					**3908M**	**218**	

Production Experiments

3. IAM

   a. RCP 8.5 GLM vs. Direct IAM land use (3 IAMs)
   The four RCPs each include global, spatially explicit land use scenarios for the 21st century, and each RCP was produced by a different IAM. To produce a more uniform set of inputs for earth system models, IAM-specific land use projections were harmonized by using a single model, the Global Land Model (GLM), to convert and normalize them into land use scenarios with a common set of land cover categories, transitions between types, and spatial resolution. CMIP5 CESM runs and associated analysis has already demonstrated that this harmonization process can in fact introduce biases in the land use simulated within CESM, particularly regarding wood harvest, with serious consequences for the carbon cycle. We propose a set of experiments which would compare the consequences of direct implementation of land use patterns from IAMs into CLM with GLM-harmonized land use patterns. The result of this study would be a new set of recommendations for improved process of linking IAM land use scenarios with CESM and earth system models more broadly. We propose experiments with land use patterns from three different IAMs, using the CESM configuration B_1850_CN,(0.9x1.25_gx1v6).

   b. RCP-based regional land use feedback (3 regions)
   To investigate the potential magnitude of regional land-climate feedbacks, we propose a coordinated set of experiments that would investigate the one-directional influence of land use on regional climate, and, separately, the one-directional influence of climate on regional land use decisions in IAMs. Results would help prioritize which types of feedbacks may warrant further work on full coupling of IAMs and CESM in order to adequately capture such feedbacks. We propose investigating feedbacks in three regions, for example the Amazon forest region, high latitude forest regions, and the African tropics. In each case, one or more IAMs would generate a set of alternative spatial patterns of land use for that region. CESM runs would be carried out to investigate the sensitivity of climate and land cover outcomes to these alternative land use patterns. Output from these runs would then be used to drive IAMs, to investigate whether the differences in biophysical outcomes would be large enough to have consequences on land use decisions.

c. <u>RCP-based air quality-atmospheric chemistry</u>
These experiments will provide exploratory analysis in order to inform the development of working group activities in a new area, air quality, identified as a priority area in the working group white paper. We propose to investigate the sensitivity of regional climate and atmospheric chemistry to plausible alternative scenarios of short lived emissions relative to one or more RCPs. Results will be used to prioritize the focus of future working group activities in this area.

d. <u>RCP-based iESM simulations</u>
Along with investigation of one-way influences between IAMs and CESM, we propose a set of simulations with iESM to investigate fully coupled simulations within the same experimental designs as those described above. We separate the request for iESM computing time given its different model configuration. iESM couples CESM to the GCAM integrated assessment model developed at the DOE/PNNL/Univ. of Maryland Joint Global Change Research Institute. These simulations will illustrate the relative costs and benefits of fully coupled vs. one-way interactions between IAMs and CESM. In addition, they will be useful in scoping the issues involved in modifying the software coupling infrastructure developed for iESM for use more broadly by the IAM community.

<u>Water</u>
4A & 4B) Simulations of the Impact of Climate Change on the Precipitation systems in the US
Validating the improvements in the development section will be carried out by simulating the impact of climate change on with the major precipitation phenomenon in the United States: a) the American Monsoon and 2) Droughts in the American Southwest. For each of these, five member ensemble simulations using the 1° CESM from year 1850 to 2099 will be carried out. The strong emphasis on short timescales and extremes means that some practical matters will need to be addressed, such as how to save or estimate the required extreme climate variables from the climate simulations without generating data volumes too big to be usable.

Experiment	Model Configuration	# runs	# of years	Core hour / year	Total core-hours	Total data volume in TB	Priority
3A GLM vs. Direct IAM land use	B_1850_CN (0.9x1.25_gx1v6)	20	100	295	590320	39	BC
3B regional land use feedback	B_1850_CN (0.9x1.25_gx1v6)	20	100	295	590320	39	A
3C iESM simulations	B_1850_CAM5 (0.9x1.25_gx1v6)	12	100	910	1092000	32	A
3D air quality-atmospheric chemistry	B_1degree_CAM5 _STRATTROP	4	100	2000	800000	20	BC
4A Monsoon	B, CESM 1°	5	250	910	1137500	33	BC
4B Drought	B, CESM 1°	5	250	910	1137500	33	A
Total					**5.348M**	**196**	

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Software Engineering Working Group

Research Plan and Broad Overview Objective

The role of the Software Engineering Working Group (SEWG) is to coordinate the computational development of the CESM model components, oversee the evolving design of the CESM as new model components, new model grids and new model physics are added to the system and at the same time engineer the model system to obtain optimal throughput and efficiency. This is becoming particularly challenging as the number of model configurations and resolutions are rapidly increasing. The SEWG is also responsible for overseeing CESM releases. Since January 2009, it has provided 4 major releases to the CESM community. These releases 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 SEWG 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 CESM1 was 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 CESM1 to the user community, periodic creation of release updates now requires extensive testing of the release code base.

The SEWG 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. About 5-10 simulations are normally required to achieve optimal load balance for the run. 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 64 bluefire tests to ensure reliability on CSL production machines. Each test type is often run in more than one resolution, with more than one set of compiler options (such as activating bounds checking and other debug features) 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 slowdowns 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.

  The test parameter space has recently dramatically increased. A few examples are the introduction of a new land ice sheet component, the inclusion of WACCMX in CAM, the addition of a new wave component, and a new capability to now run multiple instances of a given component out of a the single executable. This last feature is now leveraged by DART data assimilation. In addition, the model system is now targeting much higher resolution grids along with new grid types. In particular, new capability is now available to run CAM and CLM on unstructured grids, including locally refined grids. Finally, along with the addition of new model physics and dynamical cores, the resulting 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.

Proposed Experiments and Computational Requirements

Development Experiments

- *Testing*

  Currently running a single instance of the CESM test suite requires 4000 core-hours. However, as we target the new model development challenges outlined above, particularly the higher resolution configurations, we expect at least a factor of 10x increase in our testing requirements. As a result, we request 400,000 core-hours/month for CESM testing. This would permit us to target 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 30,000 core-hours/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 20,000 core-hours/month for resolving unexpected system issues.

Total for development is 450,000 core-hours/month for a total of 8.1 million core-hours over the lifetime of this proposal.

Whole Atmosphere Working Group

Research Plan and Broad Overview of Objectives

The goal of the whole atmosphere working group (WAWG) is to facilitate continued development of the Whole Atmosphere Community Climate Model (WACCM) as an integral part of CESM, and to use WACCM to understand the couplings between atmospheric layers, the role of chemical, physical and dynamical processes in defining these couplings, the implications of these couplings for space weather and climate, and the interaction between the Earth's atmosphere and the Sun. WACCM simulations will be used to study the effects of stratosphere on tropospheric climate and to support the CCMVal3 assessment efforts; to elucidate the atmospheric responses to various interannual forcings, such as solar cycle, ENSO, volcanic eruption, and quasi-biennial oscillation; to examine the terrestrial impacts of asteroids; and to assess the effects of geo-engineering proposals to mitigate climate change. Development activities intend to take advantage of recent improvements in physical processes in CAM5, the new spectral element dynamical core, and the significant increase in computing power enabled by the NCAR-Wyoming Supercomputing Center (NWSC); add new capability to the model, and address deficiencies in WACCM.

Development Objectives

There are several known biases/deficiencies in current WACCM, including the absence of quasi-biennial oscillation (QBO) in equatorial stratospheric winds, the cold bias of the southern polar stratosphere during winter, the late breakdown of the southern polar vortex and recovery of ozone, and the warm bias of the mesopause. These biases may all be related to gravity wave (GW) forcing, as demonstrated by our recent studies. Further development and improvement of the GW parameterization will focus on several aspects: i) correcting the mesopause warm bias; ii) properly accounting for the effects of molecular diffusion in the parameterization; iii) adding a second spectrum of gravity waves with typical wavelength ~1000 km. The implementation of these ideas globally is expected to be crucial for driving quasi-biennial oscillation (QBO) and resolving the WACCM cold-pole problem in the Southern Hemisphere.

Atmospheric thermal tides are critical for upper atmosphere variability, but their amplitude and spatial structures are small or biased in WACCM. The amplitude of tides in WACCM is too small by about a factor of two and the tides have vertical wavelengths longer than observed. We will investigate tidal damping or vertical structure changes due to gravity waves within the mesosphere, the impact of the mean winds in the tropical middle atmosphere on tidal generation and propagation, and the potential for enhanced vertical resolution to improve tidal simulations.

We plan to develop and test WACCM-SE (spectral element version of WACCM) at ne30 and ne120 (150 levels), corresponding roughly to 1° and $1/4^{o}$ horizontal resolution. We will couple WACCM chemistry to the conservative semi-Lagrangian multi-tracer transport scheme (CSLAM) developed for the cubed-sphere SE dycore. The high-resolution simulation will resolve mesoscale gravity waves from the troposphere to the thermosphere and ionosphere, which is critical for space weather applications of WACCM. This will also be used for validation of the gravity wave parameterization, which is needed for long-term climate simulations and the poor representation could lead to biases as mentioned above.

The current volcanic heating approach in CAM4 overestimates the heating for large volcanic eruptions (e.g., Agung, El Chichón, and Mt Pinatubo). This issue is related to a mismatch between the derivation of the H_2SO_4 mass and composition in the chemistry routine and the optics used in the radiative transfer module (CAMRT). The new volcanic heating approach will use the CAM5 RRTMG radiative transfer module. We will be developing and testing the new approach within the WACCM5 model over a historical period that includes three large volcanic eruptions.

WACCM-X (WACCM extended to the thermosphere) will be released soon with CESM1.0.4. New development will focus on ionospheric physics. The ionospheric plasma energy equations solver has been completed; the next goal is to implement the vertical plasma transport module, including the ambipolar diffusion and field-aligned advection. Another WACCM-X development will be the inclusion of horizontal molecular diffusion, which becomes comparable with the vertical diffusion as the model resolution increases. Horizontal diffusion is supported by the HOMME model infrastructure.

We anticipate increasing community demand for the specified chemistry (SC) version of WACCM4. We will develop compsets for running SC-WACCM under control and transient conditions, and run these scenarios to develop initial conditions for community distribution. We will compare the climate predicted by SC-WACCM to that from WACCM with full chemistry. We will also continue development of WACCM5, adding a prescribed version of the modal aerosol model (MAM) from CAM5, and the option for running prognostic MAM.

In preparation for studies of stratospheric aerosol, volcanic eruptions, meteor impacts and polar mesospheric clouds (PMCs), we will tune, test, and debug WACCM/CARMA models for stratospheric sulfate, dust, and black carbon (BC). We will develop schemes for sub-gridscale gravity wave temperature perturbations, and particle heating.

Production Objectives

Observations and WACCM show atmospheric variability that correlates with external forcing of the atmosphere such as the 11-year solar cycle, ENSO, volcanic eruption, and the QBO. We propose to conduct and analyze multiyear WACCM simulations with one or more of these forcing processes activated to separate the atmospheric response to each of these sources of interannual variability and to identify aliased signals, and determine the length of a data record necessary for making such a distinction.

Recent work for AR5 suggests that WACCM produces different patterns of tropospheric regional climate change than does CAM. It is believed that the difference is related to the behavior of the wintertime stratosphere and, in particular, to the climatology of SSW in the Northern Hemisphere. We propose to examine the impact of various model parameters on the simulation of tropospheric climate change, in particular the role of the turbulent mountain stress parameterization and the impact of horizontal resolution.

Over the next two years new CCMVal3 Chemistry Climate Model simulations will be designed to examine ozone depletion and recovery trends, building on the current IPCC AR5 simulations; in addition, these new simulations will have a more detailed representation of tropospheric processes.

We propose to extend previous work on oceanic impacts of asteroids (Pierazzo et al., 2010) by considering the effects of an impact on land. In addition to chemical perturbations due to the injection of NOx, H2O, etc. into the upper atmosphere, the effect of dust from the impact and soot from resulting fires will also be considered by using WACCM coupled to the CARMA microphysical model (Bardeen et al., 2008). We also propose to simulate the large asteroid impact that occurred 65 Ma in Yucatán and resulted in the Chicxulub crater (Swisher et al., 1992) and is thought to have been responsible for mass extinction (Alvarez et al., 1980). This impact occurred over land and shallow water, so the material injected will be a combination of those considered in our first two studies. We will look at 2 cases, one where the ejecta follows a purely ballistic distribution and another where the ejecta follows a "postballistic skidding" pattern (Artemieva and Morgan, Icarus, 2009).

PMC were first detected following the eruption of Krakatau in 1885. Thomas et al., (1989) speculate that this eruption added sufficient water in the mesosphere for the PMC to become visible; however, these observations may have been part of the general trend in increased PMC brightness that has been detected in recent times (Deland et al. 2007) combined with more intensive viewing of the evening sky. We will simulate this onset period of PMC with and without water vapor injected from the Krakatau volcano.

We have recently completed SD-WACCM/MERRA simulation (1988-present day) to examine model physical, dynamical, and chemical processes in the polar stratospheric and UTLS region of the atmosphere. With nascent extension of the reanalysis data product from the NASA Global Modeling and Assimilation Office (GMAO) Model-Era Retrospective Analysis for Research and Applications (MERRA) back to 1979 and its meteorological fields at a higher resolution (~0.5 deg), we propose repeat this simulation accordingly. Results from this simulation will be compared to a full interactive version of WACCM at the same resolution and over the same historical period and to previous SD-WACCM runs at 2°.

MERRA (Model-Era Retrospective Analysis for Research and Applications) temperature, zonal and meridional winds, and surface pressure at 0.5° resolution will be used to "nudge" WACCM, starting in year 1979. Results from this simulation will be compared to a fully interactive version of WACCM at the same resolution and over the same historical period and to previous SD-WACCM runs at 2°.

We propose a study to investigate the influence of solar spectral irradiance variability on WACCM and to understand WACCM's sensitivity in using a standard solar irradiance model in the CMIP5 simulations. This study is part of a multi-model SPARC-SOLARIS investigation.

As part of Atmospheric Processes controlling Stratospheric Sulfur and Aerosols and their Role in Climate (APSiC), a recently initiated SPARC activity, we will use WACCM-CARMA to investigate processes controlling stratospheric sulfate. We will also use WACCM-CARMA to investigate the consequences of future geoengineering through solar radiation management by enhancing stratospheric sulfate.

Proposed Runs and Computational Requirements

Development Experiments

Revise and update the WACCM gravity wave parameterization

The significant complexities of gravity wave parameterization development and tuning will require 250 model years.

Improved Volcanic Heating Specification

We will simulate the period 1950-2005, covering three volcanic eruptions, repeating 10 times with varying parameters for aerosol heating.

Development and testing of WACCM-SE at nominal and high resolution

We will run SC-WACCM-SE at high resolution (ne120) for 5 years, and at nominal resolution (ne30) for 5x20 years. We will run WACCM-SE with CSLAM for 5x20 years.

Improve amplitude and vertical structure of tides

We will run WACCM for 60 years for development and testing.

WACCM-X Development: Vertical plasma transport and horizontal molecular diffusion

We will run WACCM-X-SE for 1 year.

SC-WACCM development and validation

We will perform pre-industrial and transient simulations paralleling our CMIP5 runs to compare with the latter. We will tune and balance our 1850 control (300y), followed by 200y for the control simulation. We will run an ensemble of 3 transient runs from 1850 to 2005 with annually varying solar input, and an ensemble of 3 transient runs from 1955 to 2005 with daily varying solar input, paralleling our CMIP5 runs.

WACCM5 development

We will tune WACCM5, starting with a balanced TOA radiative condition for our 1850 control scenario. Once balanced conditions are reached, we will branch for a transient run to 1955, perform an ensemble of 3 simulations for 1995-2005, and continue the control run for an additional 200 years for comparison to transient simulations.

WACCM-CARMA development

Development and tuning of WACCM-CARMA models will require 10x15y for sulfates, 6x10y for dust-BC, 6x15y for dust-BC-sulfate, 4x10y for sub-gridscale GW temperature perturbations, and 4x10y for particle heating.

Experiment	Model Configuration	# runs	# of years	Core hour / year	Total core-hours	Total data volume in TB	Priority
GW parameterization	W4/2°	1	250	670	167,500	1	A
Volcano heating	W5/2°	10	55	870	478,500	1.2	A
SC-WACCM-SE hi-res	W5/SE/SC/ ne120/L150	1	5	113,000	565,000	55.00	C
SC-WACCM-SE tuning and validation	W4/SE/ne30	5	20	993	99,259	4	A
WACCM-SE tuning and validation with CSLAM	W4/SE/ne30/CSLAM	5	20	2,680	268,000	10	A
WACCM-X development	W4/SE ne30 /L81	1	1	4,000	4,000	0.17	A
Atmospheric tides	W5/2° /L125	1	60	1,740	104,400	0.26	A
WACCM5 development	W5/2° 1850	1	500	870	435,000	2	A
WACCM5 development	W5/2° 1850-2005	3	155	870	404,550	2	A
WACCM5 development	W5/2° 1955-2005	3	50	870	130,500	0.7	C
SC-WACCM development & validation	W4/SC/2° 1850	1	500	250	57,500	1	A
SC-WACCM development & validation	W4/SC/2° 1850-2005	3	155	250	116,250	2	C
SC-WACCM development & validation	W4/SC/2° 1955-2005	3	50	250	37,500	0.7	A
WACCM4 1° tuning and validation	W4/1°	5	55	2680	737,000	11	B
WACCM/CARMA sulfate development and tuning	W4/RRTMG/CARMA-sulfate/2°	10	15	2,250	337,500	1.5	A
WACCM/CARMA dust and BC aerosol development and tuning	W4/RRTMG/CARMA-dust-BC/2°	6	10	2,250	135,000	1.5	A
WACCM/CARMA dust, BC, and sulfate aerosol development and tuning	W4/RRTMG/CARMA-sulfates-dust-BC 2°	6	15	6,750	607,500	1.5	A

WACCM/CARMA sub-gridscale GW temperature perturbation development and tuning	W4/RRTMG/CARMA-PMC 2°/L125	4	10	2,010	80,400	1.5	A
WACCM/CARMA particle heating	W4/RRTMG/CARMA-PMC 2°/L125	4	10	2,010	80,400	0.7	B
Total					**4.913M**	**95.53**	

Production Experiments

Climate sensitivity in WACCM

We propose to evaluate the climate sensitivity of WACCM by performing the following runs:

- Calculate the transient climate response (TCR), i.e. the change in climate relative to a pre-industrial control simulation for years 61–80 of a transient simulation in which there is a 1% per year CO2 increase.
- Determine the change in equilibrated climate of a 2 x CO2 simulation compared to pre-industrial control with atmosphere coupled to slab ocean.
- Calculate the evolution of climate relative to a pre-industrial control in a simulation with a deep ocean model where CO2 has been increased to 4x pre-industrial levels. All simulations will be compared to comparable ‘low-top’ CCM4 simulations to investigate the influence of the stratosphere on climate sensitivity.

The role of the stratosphere in climate

WACCM reproduces reasonably well many features of the climatology of stratospheric sudden warmings (SSW) and of tropospheric blocking, and the relationship between de two (de la Torre et al, *JGR*, 2012, in press). Recent work for AR5 suggests that WACCM produces different patterns of tropospheric regional climate change than does CAM. The difference may be related to the behavior of the wintertime stratosphere and, in particular, to SSW in the Northern Hemisphere. We propose to examine the impact of various model processes on the simulation of tropospheric climate change, as follows:

- Evaluate the role of the turbulent mountain stress parameterization, with emphasis on its contribution to the momentum budget of zonally asymmetric motions, in particular planetary waves
- Examine the impact of ENSO events on the frequency of stratospheric sudden warmings, and the effects of the latter on tropospheric climate using simulations with climatological SST
- Compare differences in the simulation of climate change between high-top and low-top models at 1°

Assessment: CCMVal3

We will run WACCM5 at 1° with 125 species for 10x150y runs for CCMVal3 experiments.

Effects of impacts by asteroids

We will run WACCM/CARMA to simulate the dust and BC resulting from mid-sized (3x10y) and large-sized (3x15y) asteroid impacts. We will run WACCM/CARMA to simulate sulfates, dust and BC from the K/T impact (3x10y).

Role of Krakatau in first detection of polar mesospheric clouds (PMC)

We will run WACCM/CARMA to simulate PMC formation (4x30y) following the eruption of Krakatau.

Hindcast simulations using SD-WACCM4/MERRA

MERRA (Model-Era Retrospective Analysis for Research and Applications) temperature, zonal and meridional winds, and surface pressure at 0.5° resolution will be used to "nudge" WACCM, starting in year 1979. Results from this simulation will be compared to a fully interactive version of WACCM at the same resolution and over the same historical period and to previous SD-WACCM runs at 2°.

Solar influence on climate

We will run three 30-year runs with perpetual-year-2000 GHG/ODS conditions and fixed solar forcing based on NRLSSI and SORCE SSI solar maximum and solar minimum spectra.

SPARC stratospheric aerosol assessment (APSiC)

We will run SD-WACCM-CARMA for the period 1996-2011 with input from small volcanic eruptions during that period, as well as inventories of sulfur emissions from surface pollution. We will perform two additional parallel runs, one without volcanic input, and one with constant surface emissions, to evaluate the relative importance of each to the stratospheric aerosol budget.

Geoengineering simulations

We will run two ensembles of three runs for the years 2020-2070, with increasing OCS from surface emissions in one ensemble and direct stratospheric injection of SO_2 in the other. We will compare the effectiveness and impacts of each technique on climate and stratospheric chemistry.

Real and aliased response of the atmosphere to interannual forcing

We will run WACCM5 at 2° for an ensemble of 6x50y runs, varying forcings.

Experiment	**Model Configuration**	**# runs**	**# of years**	**Core hour / year**	**Total core-hours**	**Total data volume in TB**	**Priority**
Mid-size asteroids impacts	W4/RRTMG/CARMA-dust-BC 2°	3	10	2,250	67,500	0.13	A
Large-size asteroids impacts	W4/RRTMG/CARMA-dust-BC 2°	3	15	2,250	101,250	0.20	A
K/T asteroid impacts	W4/RRTMG/CARMA-sulfates-dust-BC 2°	3	15	6,750	303,750	0.07	B
Krakatau and PMCs	W4/RRTMG/CARMA-PMC 2°/L125	4	30	2,010	241,200	0.50	A
SD-WACCM/MERRA hindcast	W5/SD/125sp/0.5°/L88	1	33	20,000	660,000	100.00	A
WACCM control for hindcast	W5/125sp/0.5°/L66	1	62	20,000	1,240,000	100.00	A
CCMVal	W5/125sp/1°/L66	10	150	5,600	8,400,000	150.00	ABC
Real and alias responses	W5/2°	6	50	870	261,000	1.30	A
Climate sensitivity in WACCM	W4/2°	1	80	670	53,600	0.32	A
Climate sensitivity in WACCM	W4/2°	1	60	670	40,200	0.24	A

Climate sensitivity in WACCM	W4/2°	1	250	670	167,500	1.00	A
Role of stratosphere in troposphere climate	W4/1°	1	100	2,680	268,000	4.00	A
Role of stratosphere in troposphere climate	W4/2°	3	45	670	90,450	0.50	A
Role of stratosphere in troposphere climate	W4/1°	1	345	2,680	924,600	14.00	A
Solar influence	W4/2°	3	30	670	60,300	0.40	A
Stratospheric aerosol assessment	W4/RRTMG/CARMA-sulfate/2°	3	15	2,250	101,250	2.00	A
Geoengineering science	W4/RRTMG/CARMA-sulfate/2°	6	50	2,250	675,000	2.00	A
Total					**13.656M**	**376.66**	

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