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The use of the Climate-science Computational End Station (CCES) development and grand challenge team for the next IPCC assessment: an operational plan

W M Washington1, J Drake2, L Buja1, D Anderson3, D Bader4, R Dickinson5, D Erickson2, P Gent1, S Ghan6, P Jones7 and R Jacob8

1National Center for Atmospheric Research, Boulder, CO 80837, USA
2Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA
3NASA Headquarters, Washington, DC 20024, USA
4Lawrence Livermore National Laboratory, Livermore, CA 94550, USA
5Georgia Institute of Technology, Atlanta, GA 30332, USA
6Pacific Northwest National Laboratory, Richland, WA 99352, USA
7Los Alamos National Laboratory, Los Alamos, NM 87545, USA
8Argonne National Laboratory, Argonne, IL 60439, USA

E-mail: wmw@ucar.edu

Abstract. The grand challenge of climate change science is to predict future climates based on scenarios of anthropogenic emissions and other changes resulting from options in energy and development policies. Addressing this challenge requires a Climate Science Computational End Station consisting of a sustained climate model research, development, and application program combined with world-class DOE leadership computing resources to enable advanced computational simulation of the Earth system. This project provides the primary computer allocations for the DOE SciDAC and Climate Change Prediction Program. It builds on the successful interagency collaboration of the National Science and the U.S. Department of Energy in developing and applying the Community Climate System Model (CCSM) for climate change science. It also includes collaboration with the National Aeronautics and Space Administration in carbon data assimilation and university partners with expertise in high-end computational climate research.

1. Introduction

The creation of computational end stations provides the scientific applications software and world-class computational resources needed for researchers in various areas of science. In its fourth year, the Climate Science Computational End Station (CCES) advances climate science through both an aggressive model development activity and an extensive suite of climate model application simulations. Subproject allocations are subject to external scientific review of specific proposed computational experiments. The required computing resources and the scientific goals of the proposed CCES are compatible and consistent with the DOE Office of Science Strategic Plan, the Federal Climate Change Science Program (CCSP) Strategic Plan, and the CCSM Strategic Business Plan for 2004–2008 and with the CCSM Science Plan (http://www.ccsm.ucar.edu).

This multiyear project includes an ambitious simulation plan emphasizing model application with an ongoing core model development that envisions future needs and scales the CCSM for use on petascale computer systems. The CCSM3 is the current state-of-the-science model that accurately simulates global to continental aspects of the physical climate system. Extensive simulations with higher resolution versions of the current model are under investigation to identify and correct bias errors that are unacceptable for future simulations that require subcontinental and smaller-scale accuracy. Using high-resolution ocean and ice models, researchers also plan studies of abrupt climate change, in which large global scale changes occur within a few decades.

The CCSM3 requires the specification of changes to many factors that determine climate change, such as the atmospheric concentrations of greenhouse gases, atmospheric aerosols, and the distribution of
vegetation types on the land surface. In the Earth system version of CCSM, these factors result from dynamic physical, chemical and biological processes. These are being added to the current CCSM4 as part of this project, and will be used in future versions to realistically predict future climates. Significant biogeochemical cycles influencing climate change involve carbon, sulfur, and nitrogen cycles. Of particular importance to U.S. energy policy is the correct simulation of the global carbon cycle and its feedbacks to the climate system, including its variability and modulation by ocean and land ecosystems. This continuing model development and extensive testing of the CCSM system to include recent new knowledge about these processes is at the cutting edge of climate science research and is a principal focus of the CCES. We are planning to develop CCSM4 in time for the fifth IPCC assessment.

The CCES predicts future climates using emissions scenarios and other changes resulting from energy policies options. We deliver simulations improving the scientific basis, accuracy and fidelity of climate models and perform climate change simulations that directly inform national and international science policy, thereby contributing to the DOE, NSF, and NASA science missions.

2. Resources
The Computational Climate End Station manages resources on the three primary systems that fall under the INCITE program: Cray XT4 Jaguar at NCCS, the Cray XT4 Franklin at NERSC, and the IBM Blue Gene/P at Argonne. The CCES seeks to provide a single source version of the CCSM that runs on all these platforms and that can be used for applied research in climate change. Development time for model extension, validation, and verification, and software scalability forms a significant part of the requested allocation on each platform. The experiments and simulations use all these machines, demonstrating production on cutting-edge high-performance computer (HPC) platforms and taking advantage of the unprecedented computational power for more comprehensive, high resolution climate prediction results. The Earth System Grid infrastructure links climate simulation data and analysis capabilities across the DOE laboratories and NCAR.

3. Brief summaries of subprojects
The CCES is the primary allocation that develops and deploys the Community Climate System Model (CCSM) for use in DOE and NSF climate change simulation experiments. The CCSM is the primary computational instrument. We provide the capability tools and simulation frameworks needed to advance climate-change science and carry out leading climate-science research program in conjunction with our partners and sponsoring agency programs. We execute the high-priority simulations for the DOE that require the high-end computational capability of scalable high-performance computers. In addition, we provide outreach to the larger research community through simulation products analysis of model results, and workshops.

2.1 Climate change (NCAR/LLNL)
The Climate Change Working Group and the climate modeling community has initiated an experimental design process for the next round of coordinated climate change experiments that will involve atmosphere-ocean general circulation models (AOGCMs) and Earth system models (ESMs) for assessment in the IPCC Fifth Assessment Report in 2013. In consultation with the Integrated Assessment Modeling community that formulates scenarios, a set of climate change experiments and scenarios is proposed that will address both short-term climate change (out to about 2030), with high-resolution coupled models (0.5–1.0 degrees horizontal resolution in the atmosphere) to look at regional climate change and processes involved with producing changes of weather and climate extremes, and long-term climate change (out to 2300) with medium-resolution coupled models (about 1.5–2.0 degrees horizontal resolution in the atmosphere) to quantify feedbacks involved with carbon cycle and to assess climate change adaptation in mitigation scenario experiments. We are planning future climate change simulations to the year 2300, short-term high-resolution climate predictions, coupled ice sheet simulations, and 1000-year biogeochemistry simulations. The simulation data is freely and openly provided to the international climate science community via the Earth System Grid.
2.1 SciDAC biogeochemistry (LLNL/PNNL/ORNL/NCAR/LANL)

The SciDAC Biogeochemistry subproject focuses on the impacts of land use change and dynamic global vegetation on the climate system. This is a follow-on phase to the Carbon-Land Model Intercomparison Project (C-LAMP) and the C4MIP model analysis and evaluation projects. It is hoped that this will be instrumental in defining the biogeochemical/carbon experiments for the IPCC AR5. This will assess the performance using observational datasets of the CLM-CN, CASA, and IBIS models in the CCSM framework to gauge the strength of the feedback between the carbon cycle and the climate system.

2.2 SciDAC Earth system model with sulfur (NASA/ORNL)

As part of the SciDAC CCSM Consortium project, a groundbreaking Earth system model simulation (and model development), is being carried out. The model focuses on dimethyl sulfide interactions to extend and augment the current plans of the CCSM Biogeochemistry working group by focusing on the sulfur cycle and aerosol feedbacks. The simulations will also be used as a testbed for atmospheric chemistry, particularly new aerosol indirect effects.

2.3 NASA carbon assimilation (ORNL)

Our NASA team is pursuing the simulation and assimilation of atmospheric carbon species. Carbon modeling and use of observational data are considered key to the long-term success of the End Station’s modeling thrust. This project is performing multiyear data assimilation simulations of atmospheric carbon species at 0.5-degree spatial resolution using the GEOS-5 atmospheric general circulation model. The runs use specified emission boundary fluxes for CO and CO₂.

2.4 Eddy-resolving Parallel Ocean Program (LANL/SIO/NCAR)

The Parallel Ocean Program (POP) ocean model is being used to produce climate simulations with ocean mesoscale eddies (~20 km in size) and small-scale topographic features. These play an important role in determining the structure of important current systems in the ocean and in the eddy transport of heat. Previous simulations have shown that high-resolution (0.1° or less) is required to adequately represent properties of ocean current systems such as that of the Gulf Stream, with its separation at Cape Hatteras and subsequent turn to the northwest near the Grand Banks. At coarser resolutions, it has been impossible to reproduce such features, resulting in significant biases that can strongly distort important feedbacks in the climate system. This version uses a new configuration with a tripole grid and partial bottom cells and also attempts to introduce an improved advection scheme. This high-resolution, standalone, coupled ocean/ice simulation set the stage for a fully coupled climate simulation with the eddy-resolving ocean as a high-priority SciDAC project.

2.5 Community Atmosphere Model development (NCAR/LBL/LLNL/PNNL/LANL/ORNL)

High-resolution configurations of the Community Atmosphere Model (CAM3) and prototype CAM4 have been developed to quantify the improvement in simulation fidelity across the wide range of space and time scales observed in the climate system. The development of CAM3 demonstrated a clear breakpoint in simulation quality when horizontal resolution was doubled from a 42-wavenumber truncation (T42) to an 85-wavenumber (T85) truncation. Early results suggest that the large-scale systematic biases in mean climate, which affect the quality of regional performance, are far more related to the parameterized treatment of nonresolvable physics, such as clouds, convection, radiation and boundary layer. Some transient features of the simulation are far more realistic, including the clear presence of tropical storms at the T341 truncation. This project investigates the spectral Eulerian dynamical core and the prototype CAM4 using the finite-volume dynamical core at resolutions as fine as 0.25 degrees, which should have solution accuracy equivalent to the T341 spectral model.

2.6 CCSM Development (NCAR/LBL/LLNL/LANL/PNNL/LANL/ORNL)

The CCSM Software Engineering Group focus is on CCSM development simulations in four main categories:
1. Model development toward CCSM version 4. CCSM Version 3.5 was assembled in June 2007, which reduced several long-standing biases in CCSM 3. The atmosphere model working group is working on incorporating the following new parameterizations: new boundary layer scheme, new shallow convection scheme, revised vertical coordinate, new aerosol microphysics package, and revised gravity wave drag scheme. The land, ocean, and sea ice components have also been upgraded.

2. Higher-resolution CCSM. Scientists at LLNL and NCAR have demonstrated that the simulation quality of the finite-volume atmosphere component improves rapidly with increasing resolution. Thus, the development versions of CCSM will be regularly tested at the higher atmosphere resolution as development is progresses toward CCSM 4.

3. CCSM3.5 with the carbon cycle. The carbon cycle includes a new land component with fully interactive carbon and nitrogen limitation, an ocean ecosystem component, and several extra fields being transported by the atmosphere component.

4. First attempts at short-term simulations using a high-resolution version of CCSM 3.5. A novel type of climate change simulation proposed for the next IPCC report is high-resolution simulations of the near future with regional climate change information. The integrations are proposed to start in 1980, run to 2005 using observed climate forcings, and then proceed to 2030 in predictive mode. Interactive chemistry will be included in some of these simulations in order to include predictive aerosols. This inclusion will enable regional simulations of pollutants near large cities to be made.

3.8 WRF resolution studies (PNNL)
Researchers are assessing the impacts of spatial resolution at cloud-resolving and mesoscale scales using regional to global configurations of the Weather Research and Forecasting (WRF) model. Recent advances in high-performance computing have made it possible to run these model configurations at very high spatial resolution down to the cloud-resolving scale over relatively large domains and long time periods. This project uses WRF to systematically assess the impacts of spatial resolution, with a focus on the model’s ability to simulate cloud processes and their interactions with the local to large scale circulation. Taking advantage of the nesting capability and cloud resolving to global modeling capability in WRF, numerical experiments using WRF configured in regional/global domains are also being performed.

3.9 University components (MIT/ORNL and Georgia Institute of Technology)
The magnitude and ubiquity of deforestation in the Amazon basin have become increasingly clear in recent years. Furthermore, there is overwhelming evidence that vegetation is not passively responding to changes in climate and weather but is dynamically evolving with climate and human and natural disturbances to vegetation. Human disturbance of Amazon forests over the next several decades is inevitable. The MIT team is taking the null hypothesis that this disturbance will have no effect on the nonlocal vegetation structure or the spatio-temporal partitioning of energy in the Amazon basin.

The Georgia Tech team is developing and testing a systematic subgrid scaling framework for the land component of the CCSM based on four elements: a complex vegetation tiling representation; an orographic tiling system; a tiling system to describe a distribution of water table parameters that derives a realistic statistical model of wetland; and an extension of our current work on precipitation intensity scaling that incorporates statistical estimation of precipitation intensities based on the physics of the CAM convective parameterization.

3.10 CCSM scaling (Argonne/Sandia National Laboratories)
Researchers at Sandia and Argonne have completed the first scaling tests with the HOMME version of CCSM CAM dynamical core. Results are encouraging: the Blue Gene/P is up to 4 times faster than other Blue Gene systems for a model with full physics and high resolution.
4. Operational plan timelines for IPCC fifth assessment simulations

Figure 1 shows the various CCSM4 model developments and production steps required to be prepared for the IPCC fifth assessment simulations (AR5). Also shown are the various organizations where the simulations will take place and the areas of programmatic emphasis with time.

Figure 1. Operational timeline.