Results from the Carbon-Land Model Intercomparison Project (C-LAMP) and Availability of the Data on the Earth System Grid (ESG)

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Abstract. This paper describes the Carbon-Land Model Intercomparison Project (C-LAMP) being carried out through a collaboration between the Community Climate System Model (CCSM) Biogeochemistry Working Group, a DOE SciDAC-2 project, and the DOE Program for Climate Model Diagnosis and Intercomparison (PCMDI). The goal of the project is to intercompare terrestrial biogeochemistry models running within the CCSM framework to determine the best set of processes to include in future versions of CCSM. As a part of the project, observational datasets are being collected and used to score the scientific performance of these models following a well-defined set of metrics. In addition, metadata standards for terrestrial biosphere models are being developed to support archival and distribution of the C-LAMP model output via the Earth System Grid (ESG). Progress toward completion of this project and preliminary results from the first set of experiments are reported.

1. Introduction

The Community Climate System Model Version 3 (CCSM3) [1] is a fully coupled climate modeling system consisting of four major component models representing the atmosphere, ocean, land surface, and sea ice. These components—the Community Atmosphere Model Version 3 (CAM3) [2; 3], the Community Land Model Version 3 (CLM3) [4; 5], the Community Sea Ice Model Version 5 (CSIM5) [6], and the Parallel Ocean Program Version 1.4.3 (POP) [7]—are linked through a coupler that exchanges mass and energy fluxes and state information among the component models. CCSM3 is designed to produce realistic simulations of Earth's mean climate over a wide range of spatial resolutions and has been used for a variety of climate sensitivity studies and climate change projections [8; 9], including projections for the recently released Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) [10]. The modeling system was developed through international collaboration and received funding from the National Science Foundation (NSF) and the Department of Energy (DOE), as well as support from the National Aeronautics and Space Administration (NASA) and the National Oceanic and Atmospheric Administration (NOAA). A large portion of DOE's recent support for CCSM has been through SciDAC projects, including the new multi-laboratory SciDAC-2 project *A Scalable and Extensible Earth System Model for Climate Change Science* led by John Drake.

For climate change research it is particularly important for the model to capture the global effects and feedbacks of carbon and other biogeochemical cycles. This need warrants directing effort toward the inclusion of atmospheric chemistry and land and ocean biogeochemistry in the component models. While a number of terrestrial and ocean carbon models have been coupled to various general circulation models (GCMs), recent work has shown that coupled interactive biogeochemical models can yield a wide range of results [11]. Since its release, three different terrestrial biogeochemistry models have been added to CCSM3. Two of these models, CASA′ and IBIS, were previously coupled to precursors of CCSM. CASA′, based on the Carnegie-Ames-Stanford Approach (CASA) biogeochemical model modified for use in global climate models [12], was formerly integrated into the Climate System Model Version 1.4 (CSM1.4) and used for a 1000-yr simulation and a variety of climate change simulations [13; 14]. IBIS is based on the Integrated Biosphere Simulator developed at the University of Wisconsin and was previously coupled to the Parallel Climate Transitional Model (PCTM) [15]. The third model, called CN for carbon-nitrogen [16], is a new model based on the uncoupled Biome-BGC model [17]. CN couples the carbon and nitrogen cycles, providing nitrogen limitation constraints on vegetation growth. CASA′ and CN are coupled to the biogeophysics of CLM3 while IBIS uses its own biogeophysics model called LSX.

2. Carbon-Land Model Intercomparison Project (C-LAMP)

In order to test the scientific performance of these terrestrial biogeochemistry modules, an intercomparison project specific to CCSM was designed and initiated by the CCSM Biogeochemistry Working Group. The goal of this CCSM Carbon-Land Model Intercomparison Project (C-LAMP) was to allow the U.S. scientific community to thoroughly test and intercompare the three terrestrial biogeochemistry models (*i.e.*, CLM3-CASA′, CLM3-CN, and LSX-IBIS) coupled to CCSM through a set of carefully crafted experiments that were similar to the Coupled Climate/Carbon Cycle Model Intercomparison Project (C^4MIP) Phase 1 protocol. However, unlike traditional model intercomparison projects, a set of well-defined metrics for comparison against best-available observational datasets was established for C-LAMP.

While these metrics will evolve as new and improved observational datasets become available, they presently include matching net primary production (NPP) from the Ecosystem Model-Data Intercomparison (EMDI) activity; correlation with MODIS (Moderate Resolution Imaging Spectroradiometer) global and latitudinal NPP; matching MODIS mean, maximum, and phase of leaf area index (LAI); matching the CO_2 seasonal cycle at NOAA flask sampling sites; correspondence with above-ground biomass estimates and below-ground carbon stocks; and matching CO_2 flux and energy measurements from global Fluxnet sites. Each model is scored based on its correspondence with these satellite and field observations. Ultimately, these scores will be used by the Working Group in making recommendations for the model processes to include in the next version of CCSM, which is expected to support simulations for the IPCC Fifth Assessment Report (AR5).

In Experiment 1, the models are forced with an improved NCEP/NCAR reanalysis climate data set [18]. For these offline runs, the objective is to examine the ability of the models to reproduce surface carbon and energy fluxes at multiple sites, and to examine the influence of climate variability, prescribed atmospheric CO_2 and nitrogen deposition, and land cover change on terrestrial carbon fluxes during the 20^{th} century and specifically during the period from 1948–2004. Experiment 1 simulations consist of the following:

Experiment 1:

1.1 Spin up run
1.2 Control run (1798–2004)
1.3 Climate varying run (1948–2004)
1.4 Climate, CO_2, and N deposition varying run (1798–2004)
1.5 Climate, CO_2, N deposition varying run with land use change (1798–2004)

In Experiment 2, energy flows between the atmosphere and terrestrial biosphere will be coupled, but for both steady state and transient parts of the experiment, the atmospheric CO_2 will be forced to follow a prescribed historical trajectory. The prescribed CO_2 will be radiatively active. The sea surface temperatures (SSTs) and ocean carbon fluxes will also be prescribed. The objective of these simulations is to examine the effect of a coupled biosphere-atmosphere for carbon fluxes and climate during the 20$^{\text{th}}$ century. Experiment 2 simulations consist of the following:

Experiment 2:

2.1 Spin up run
2.2 Control run (1800–2004)
2.3 Climate varying run (1800–2004)
2.4 Climate, CO_2, and N deposition varying run (1800–2004)
2.5 Climate, CO_2, and N deposition varying run with land use change (1800–2004)

All models will be run in the same configurations at T42 resolution (about $2.8° \times 2.8°$), using the spectral Eulerian dynamical core in CAM3 for Experiment 2. Both experiments require at least 1000-yr spin up runs, 200-yr control runs, and three climate-varying transient simulations. A combination of hourly statistics and monthly mean output fields will be saved from each model, and output from all the models will be post-processed to provide common names and units for a set of pre-determined fields to be used for the intercomparison. The complete experimental design, model configurations, output field specifications, and metrics descriptions are available on the website at http://www.climatemodeling.org/bgcmip/.

Computational resources for the C-LAMP experiments are being provided by the Computational Climate Science End Station (CCSES; Dr. Warren Washington, Principle Investigator), a Leadership Computing Facility (LCF) project awarded computing resources at the National Center for Computational Sciences (NCCS). The simulations are all being performed on the Cray X1E vector supercomputer at ORNL. Initially, the model results are being stored in the High Performance Storage System (HPSS) at ORNL; however, to increase participation by the larger scientific community in the project, model results will be distributed via the Earth System Grid (ESG) with support from the DOE Program for Climate Model Diagnosis and Intercomparison (PCMDI).

3. Project Status and Preliminary Results

To date, the CLM3-CASA′ and CLM3-CN models have been run for Experiments 1.1–1.4. The spin up runs (Experiment 1.1) required many more simulation years than expected, about 4000 instead of 500, partly due to overly stringent equilibrium criteria established in the C-LAMP protocol for carbon flux into and out of the biosphere. In total, some 10,700 model years were run resulting in about 9 TB of output being stored in HPSS. Experiments 1.5 and 2.5 will require additional software engineering to properly account for the reallocation of carbon to various pools when prescribed changes in land cover occur; therefore, these simulations will be performed at a later time. CLM3-CASA′ and CLM3-CN are now being spun up (Experiment 2.1) in preparation for the coupled simulations.

An initial 1000-yr spin up and control run of the LSX-IBIS model in the CCSM3 framework was performed. Dynamic vegetation was enabled for this run since it is required for the carbon cycle module to function. The simulated climate from this fully coupled run exhibited as much as an 8°C warm bias in parts of the Northern Hemisphere, and deciduous forest overtook many grassland areas. Additional testing and tuning of LSX-IBIS is required before it is ready to perform the C-LAMP experiments. However, because a CLM3-based model is required for future versions of CCSM, the bulk of the effort to date has been focused on CLM3-CASA′ and CLM3-CN instead of tuning LSX-IBIS.

Figure 1 contains example model-to-model comparison diagnostics for net ecosystem exchange (NEE) and NPP for the control run (Experiment 1.1). Figure 1a shows that both CLM3-CN and CLM3-CASA′ achieved steady state equilibrium with respect to CO_2 flux. The

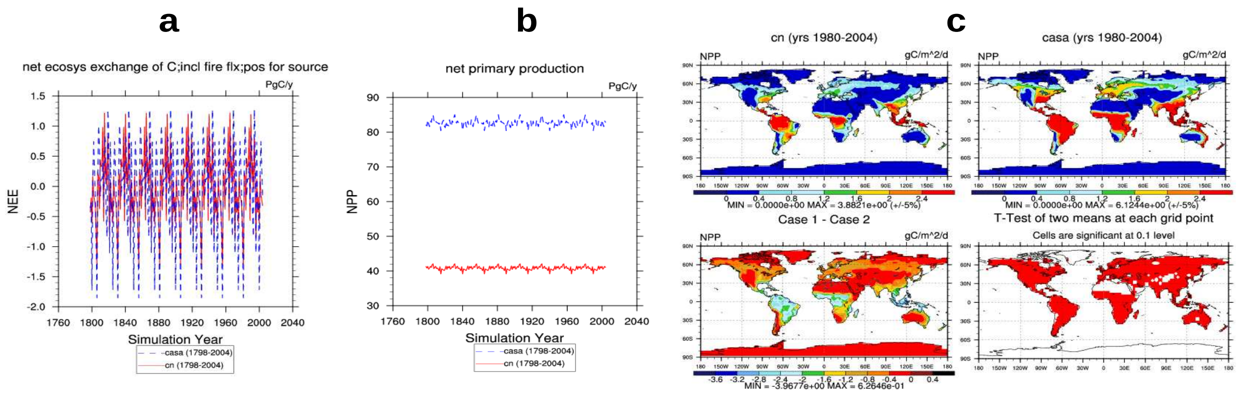

Figure 1. Example model-to-model comparison diagnostics for (a) net ecosystem exchange (NEE), (b) net primary production (NPP), and (c) distribution of annual average NPP (1980–2004) from CLM3-CN and CLM3-CASA′ for the control run (Experiment 1.1).

curves in Figure 1b show that the two models differ by about a factor of two in NPP globally, and the maps in Figure 1c show a comparison of the distribution of annual average NPP between the models for the latter portion of the model run (1980–2004). Based on global estimates, the NPP from CLM3-CASA′ is probably too high while that from CLM3-CN is probably too low.

Examples of diagnostic plots of model output compared with observations are contained in Figure 2. Figure 2a compares averaged output from the control runs (Experiment 1.1) with averaged observations of CO_2 flux, net radiation, and latent and sensible heat for the BOREAS Fluxnet site. Both CLM3-CN and CLM3-CASA′ appear to simulate the carbon and energy balance well for this site. Comparisons with other Fluxnet sites will be performed to evaluate the performance of the models under different land cover and climate conditions. Figure 2b compares the NPP from these same two models with the Ecosystem Model-Data Intercomparison (EMDI) site data for the control runs (Experiment 1.1). Both models exhibit very similar correlations with the EMDI data.

While the analysis of the transient simulations is just beginning, some differences in the models is immediately obvious. Figure 3 shows a comparison of the NEE and NPP responses from CLM3-CN and CLM3-CASA′ under varying climate, CO_2, and N deposition for years 1948–2004 (Experiment 1.4). While both biosphere models are taking up additional CO_2 (the

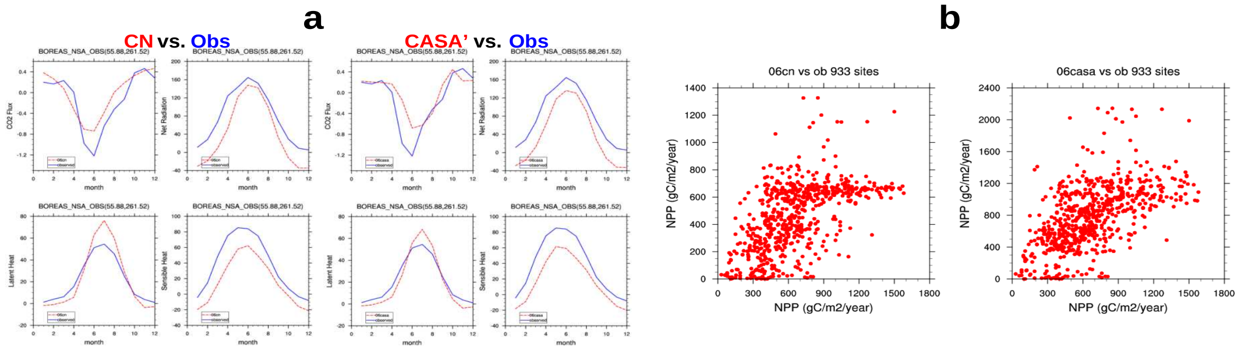

Figure 2. Example model-to-observation comparison diagnostics for (a) surface CO_2 and energy balance at the BOREAS Fluxnet site and (b) NPP at Ecosystem Model-Data Intercomparison (EMDI) sites from CLM3-CN and CLM3-CASA′ for the control run (Experiment 1.1).

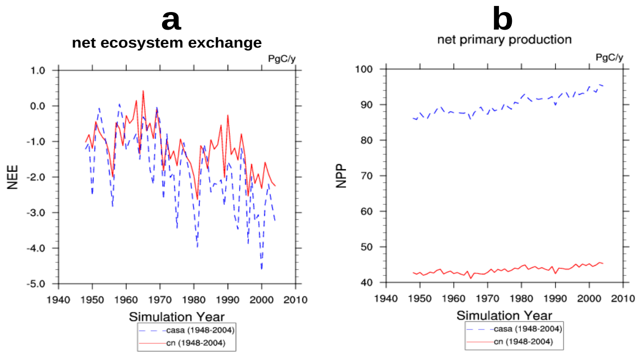

Figure 3. Example model-to-model comparison diagnostics for (a) NEE and (b) NPP for CLM3-CN and CLM3-CASA′ from the varying climate, CO_2, and N deposition run (Experiment 1.4).

land is a sink), CLM3-CASA′ exhibits a much stronger fertilization effect globally, probably because of nitrogen limitation in the CLM3-CN model that serves to constrain primary production.

Additional metrics, diagnostics, and visualizations are being developed to further investigate the performance of these models and to better explore the differences in their responses to increasing CO_2 and climate change. Visualization of atmosphere-biosphere exchanges, like the one shown in Figure 4, help to explain and demonstrate the behavior of model processes, leading to future model improvements.

4. The Earth System Grid (ESG)

As was done for IPCC AR4, the model output from the C-LAMP experiments will be made available to the wider research community through the Earth System Grid

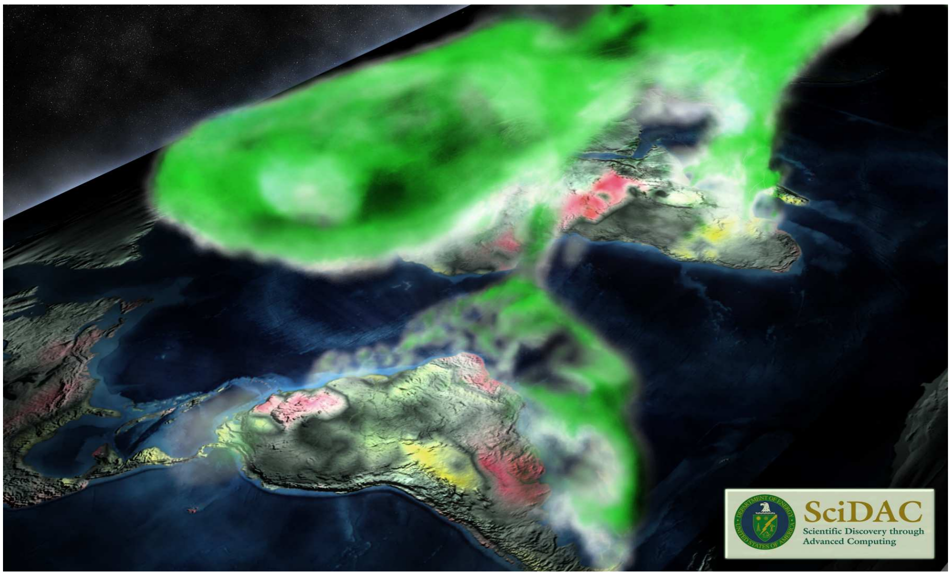

Figure 4. A snapshot from a visualization showing the CO_2 tracer from the land, the product of NEE, being advected in the atmosphere. The colors on the land surface depict NEE (green and yellow for a source, red for a sink). Visualization produced by Jamison Daniel, NCCS/ORNL.

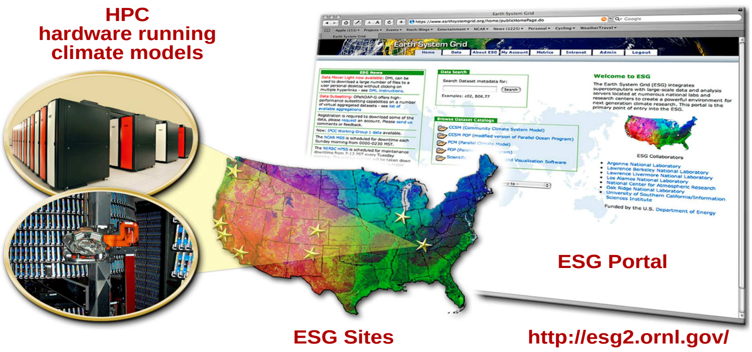

Figure 5. A new Earth System Grid portal is being established at ORNL to support C-LAMP.

Center for Enabling Technologies (ESG-CET) [19]. The Earth System Grid (ESG) (http://www.earthsystemgrid.org/) is a large, production, distributed system that allows registered users to download model output, code, and ancillary data over the Internet [20]. Two ESG Portals have been established, and a new one is being deployed at ORNL to support C-LAMP (see Figure 5). PCMDI is assisting in the deployment of this server at ORNL, which will archive and distribute the standard model output fields resulting from C-LAMP. With over 6,000 registered users and more than 250 TB of data, it was the primary means for distribution of IPCC data that resulted in over 300 scientific publications supporting AR4 [10].

C-LAMP is leading an effort to develop metadata standards for terrestrial biosphere model output. These standards will be needed to support IPCC AR5 model results since biogeochemistry and atmospheric chemistry are likely to be included in the new Earth System Models (ESMs) participating in the main simulations planned for AR5. In particular, proposals are being developed to extend the netCDF Climate and Forecast (CF) metadata conventions [21] to include better representation of common biosphere model output fields.

5. Conclusion

While only the first set of experiments has been completed, initial analysis of the C-LAMP model runs has already exposed errors in the models. Low productivity in Arctic grasslands in CLM3 and problems in the leaf area distribution in CLM3-CN were corrected in subsequent versions of the model. Many such model improvements were included in the recent public release of CLM3.5

Significant community effort has resulted in a well-defined protocol and metrics for the evaluation of terrestrial biosphere models. The international research community has expressed interest in the C-LAMP experiments, currently being carried out only for models within the CCSM3 framework. As a result, the protocol, metrics, and datasets will soon be offered to any interested research group, and PCMDI will accept model output for distribution via the ESG.

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