Terrestrial biogeochemistry in the community climate system model (CCSM)

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Abstract. Described here is the formulation of the CASA$'$ biogeochemistry model of Fung, *et al.*, which has recently been coupled to the Community Land Model Version 3 (CLM3) and the Community Climate System Model Version 3 (CCSM3). This model is presently being used for Coupled Climate/Carbon Cycle Model Intercomparison Project (C^{4}MIP) Phase 1 experiments. In addition, CASA$'$ is one of three models—in addition to CN (Thornton, *et al.*) and IBIS (Thompson, *et al.*)—that are being run within CCSM to investigate their suitability for use in climate change predictions in a future version of CCSM. All of these biogeochemistry experiments are being performed on the Computational Climate Science End Station (Dr. Warren Washington, Principle Investigator) at the National Center for Computational Sciences at Oak Ridge National Laboratory.

1. Community Climate System Model (CCSM)

The Community Climate System Model Version 3 (CCSM3) [1] is a coupled modeling system consisting of four components representing the atmosphere, ocean, land surface, and sea ice linked through a coupler that exchanges mass and energy fluxes and state information among these components. CCSM3 is designed to produce realistic simulations of Earth's mean climate over a wide range of spatial resolutions. 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 portion of DOE's support for CCSM has been through SciDAC Projects, including the multi-laboratory Climate Consortium Project headed by Phil Jones and John Drake.

Released in June 2004, this third generation coupled model includes new versions of all component models: the Community Atmosphere Model (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]. The new modeling system incorporates many improvements in the physical parameterizations which reduce or eliminate several systematic biases in the mean climate as compared with prior versions of the system. CCSM3 has been used for a variety of climate sensitivity studies and climate change projections [8, 9], and these results have contributed to the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4).

While significant model development effort has focused traditionally on improvements to the physical parameterizations and hydrodynamics, the need to provide a more complete picture of the climate system and feedbacks has directed more effort into the inclusion of atmospheric chemistry and land and ocean biogeochemistry in the component models. The global carbon cycle is of particular importance for understanding the potential for climate change. A number of terrestrial and ocean carbon models have been coupled to other general circulation models (GCMs), and recent work has shown that coupled interactive biogeochemical models can yield a wide range of results [10]. Since its release, three different terrestrial biogeochemistry models have been added to CCSM3. Two of these models—CASA' [11] and IBIS [12], were previously coupled to precursors of CCSM. The third model, called CN for carbon-nitrogen [13], is a new model based on the uncoupled Biome-BGC model. 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. CLM3-CASA' Biogeochemistry Model

The CLM3-CASA' model combines the biogeophysics of the CLM3 with the Carnegie-Ames-Stanford Approach (CASA) biogeochemical model modified for use in global climate models [14]. CASA' 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 that were recently described [11, 15]. Initially integrated into the CLM3 by co-authors John and Levis, CASA' was later modified and vectorized by Hoffman, consistent with the vectorization of CLM3 [16], for use on the Cray X1E at Oak Ridge National Laboratory.

CASA' simulates the life cycles of CLM3's plant functional types from carbon assimilation via photosynthesis, to mortality and decomposition, and the return of CO_2 to the atmosphere via microbial respiration. There are three vegetation (live) carbon pools and nine soil (dead) pools, and the rates of carbon transfer among the pools are climate sensitive. The carbon cycle is coupled to the water cycle via transpiration and to the energy cycle via dynamic leaf phenology, which affects albedo. A terrestrial CO_2 fertilization effect is possible in the model because carbon assimilation via the Rubisco enzyme is limited by internal leaf CO_2 concentrations, eventually saturating at high concentrations.

In the CASA' formulation, net primary production (NPP) is calculated from gross primary production (GPP) as computed by CLM3. NPP is allocated to the three live pools (leaf, wood, and root) with preferred allocation to roots under water-limited conditions and to leaves under light-limited conditions [17]. Turnover times of the three live pools are specific to each plant functional type, and leaf mortality of deciduous trees includes cold-drought stress to cause leaf-fall in one or two months. Leaf biomass is translated into prognostic leaf area indices (LAI) using specific leaf areas (SLA) so that LAI varies with climate. Excess carbon above the limits placed on LAI is added to litterfall.

For the nine dead carbon pools, leaf mortality contributes to metabolic and structure surface litter, root mortality contributes to metabolic and structure soil litter, and wood mortality contributes to coarse woody debris. The subsequent decomposition by microbes leads to transfer

of carbon to the dead surface and soil microbial pools as well as to the slow and passive pools. A fraction of each carbon transfer is released to the atmosphere via microbial or heterotrophic respiration. The rates of transfer are climate sensitive and are functions of soil temperature and soil moisture averaged over the top 30 cm of soil.

3. Coupled Climate/Carbon Cycle Model Intercomparison Project (C[4]MIP)

The Coupled Climate/Carbon Cycle Model Intercomparison Project (C[4]MIP) is an international project sponsored by the International Geosphere-Biosphere Programme – Global Analysis, Integration, and Modelling (IGBP-GAIM) and World Climate Research Programme – Working Group on Coupled Modelling (WCRP-WGCM) to compare coupled model results in two phases. Phase 1 is a controlled experiment using prescribed sea surface temperatures (SSTs), sea ice cover, land cover change, ocean carbon fluxes, and fossil fuel emissions with active atmosphere and land surface models exchanging CO_2 over the 20th century. Phase 2 consists of fully coupled model experiments (*i.e.*, active atmosphere, ocean, land surface, and sea ice models) with active CO_2 exchange over the 21st century.

While about a dozen modeling groups have performed fully coupled Phase 2 transient simulations—most contributing their results to the IPCC AR4—few groups have completed the more detailed partially coupled Phase 1 experiment. Modifications to the CCSM component models, including the addition of new data models, provide the capabilities needed to perform such experiments with CCSM3.1. As a result, CAM3-CLM3-CASA′ and CAM3-CLM3-CN are both being used for Phase 1 simulations at ORNL and NCAR respectively. A number of simulations have been completed at T31 resolution (about $3.75° \times 3.75°$) using the spectral Eulerian dynamical core in CAM3. See Figure 1. Additional model development is required to handle carbon accounting under prescribed land cover change following the C[4]MIP protocol prior to completing the final simulations.
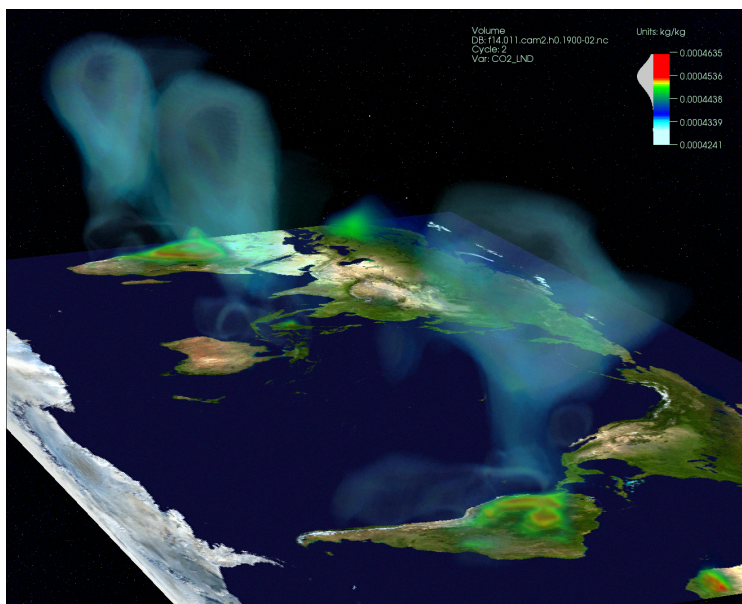
Figure 1. This image shows a snapshot of the simulated time evolution of the component of atmospheric carbon dioxide concentration originating from the land surface in February 1900. This carbon dioxide is the result of the net ecosystem exchange, the emitted CO_2 due to respiration of vegetation (autotrophs) and soil microbes (heterotrophs) minus that taken up for ecosystem production. Visualization produced by Jamison Daniel, NCCS/ORNL.

4. CCSM Carbon-Land Model Intercomparison Project (C-LAMP)

Because of the need to deliver a tested and functioning terrestrial biogeochemistry capability in the next version of CCSM by the end of calendar year 2008 to support simulations for the IPCC Fifth Assessment Report (AR5), a model intercomparison project specific to CCSM has been initiated by the CCSM Biogeochemistry Working Group. The CCSM Carbon-Land Model Intercomparison Project (C-LAMP) will allow the U.S. scientific community to thoroughly test and intercompare the three terrestrial biogeochemistry modules coupled to CCSM (*i.e.*, CLM3-CASA′, CLM3-CN, and LSX-IBIS) through a set of carefully crafted experiments that build upon the C^{4}MIP Phase 1 protocol.

In Experiment 1, the models will be 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 levels, and land cover change on terrestrial carbon fluxes during the 20th century and specifically during the period from 1948–2004.

In Experiment 2, energy flows between the atmosphere and terrestrial biosphere will be coupled, but for both steady state and transient components of the experiment, the atmospheric CO_2 will be forced to follow a prescribed trajectory. The prescribed CO_2 will be radiatively active. The 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 20th century.

All three models will be run in the same configurations at T42 resolution (about $2.8° \times 2.8°$), using the spectral Eulerian dynamical core in Experiment 2. Both experiments require 700–800-yr spin up cycles, 200-yr control runs, and three climate-varying transient simulations. A combination of hourly 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 configuration, output field specifications, and current run status are available on the website at `http://climate.ornl.gov/bgcmip`.

In order to more quickly verify and validate the three biogeochemistry models against high frequency and high quality observations, a set of offline runs for Fluxnet tower sites have been performed using CLM3-CASA′ and CLM3-CN. These experiments have also served to identify issues with model spin-up, output fields, and post-processing. Running, Heinsch, and Stöckli provided observed meteorological data from eight selected Fluxnet sites (see Figure 2) for forcing the models. Certain biogeochemical, hydrological, physiological, and radiation fields have been saved hourly for intercomparison across models and with high frequency tower measurements. Analysis of these results is just beginning, and diagnostics like those shown in Figure 3 are being provided on a website for community evaluation. The IBIS model will also be included in these point validation runs once the code has been modified to read the meteorological forcing data.

C-LAMP is the first Biogeochemistry Subproject of 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 C-LAMP experiments are already underway on the Cray X1E at ORNL, and preliminary results are expected by the end of calendar year 2006. To increase participation by the larger scientific community, model results will be distributed via the Earth System Grid (ESG). The DOE Program for Climate Model Diagnosis and Intercomparison (PCMDI) has volunteered to provide support for diagnostics as well as data conversion, distribution, and archival.

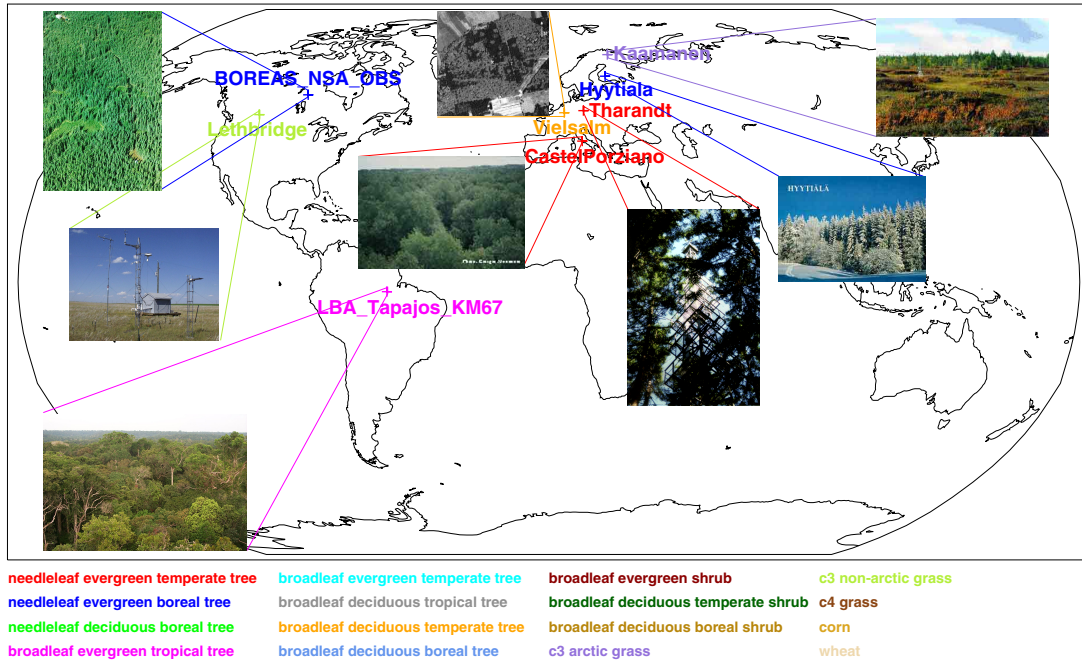**Fluxnet Tower Sites Used for Offline Model Intercomparison**

needleleaf evergreen temperate tree	**broadleaf evergreen temperate tree**	**broadleaf evergreen shrub**	**c3 non-arctic grass**
needleleaf evergreen boreal tree	broadleaf deciduous tropical tree	**broadleaf deciduous temperate shrub**	**c4 grass**
needleleaf deciduous boreal tree	**broadleaf deciduous temperate tree**	**broadleaf deciduous boreal shrub**	**corn**
broadleaf evergreen tropical tree	**broadleaf deciduous boreal tree**	**c3 arctic grass**	wheat

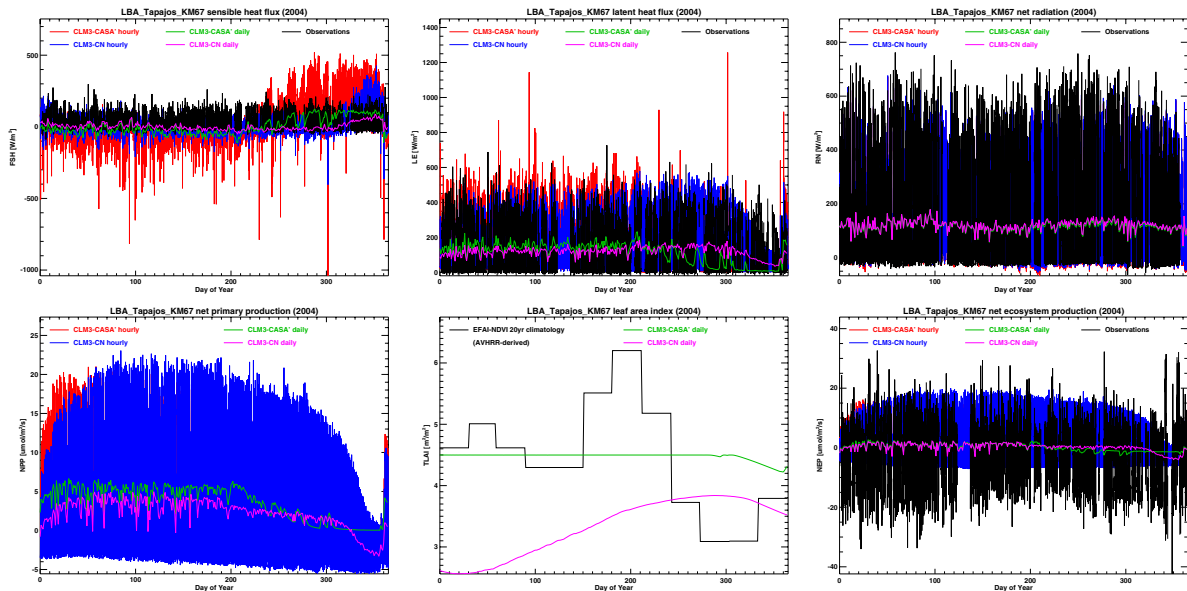**Figure 2.** Fluxnet tower sites used for offline point run model intercomparison.

Figure 3. An example of diagnostics comparing hourly simulation results from CLM3-CASA′ and CLM3-CN against flux tower observations for the LBA Tapajos KM67 Fluxnet site.

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