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The Carbon-Land Model Intercomparison Project (C-LAMP): A Protocol and Evaluation Metrics for Global Terrestrial Biogeochemistry Models

Forrest M. Hoffman [a], **James T. Randerson**[b], **Inez Y. Fung**[c], **Peter E. Thornton**[d]
Yen-Huei "Jeff" Lee[d], **Curtis C. Covey**[e], **Gordon B. Bonan**[d], **and Steven W. Running**[f]

[a]*Oak Ridge National Laboratory (ORNL), Computer Science & Mathematics Division, Oak Ridge, Tennessee, USA (forrest@climatemodeling.org)*

[b]*University of California - Irvine, Department of Earth System Science, Irvine, California, USA (jranders@uci.edu)*

[c]*University of California - Berkeley, Department of Earth & Planetary Science, Berkeley, California, USA (ifung@berkeley.edu)*

[d]*National Center for Atmospheric Research (NCAR), P.O. Box 3000, Boulder, Colorado, USA (thornton@ucar.edu, jeff@ucar.edu)*

[e]*Lawrence Livermore National Laboratory (LLNL), Program for Climate Model Diagnosis and Intercomparison (PCMDI), Livermore, California, USA (covey1@llnl.gov)*

[f]*University of Montana, Numerical Terradynamic Simulation Group (NTSG), Missoula, Montana, USA (swr@ntsg.umt.edu)*

Abstract: Described here is a protocol and accompanying metrics for evaluation of scientific model performance of global terrestrial biogeochemistry models. Developed under the auspices of the NCAR Community Climate System Model (CCSM) Biogeochemistry Working Group, the Carbon-Land Model Intercomparison Project (C-LAMP) experimental protocol improves and expands upon the Coupled Carbon Cycle-Climate Model Intercomparison Project (C^4MIP) Phase 1 protocol. However, unlike traditional model intercomparisons, C-LAMP has established scientific model performance metrics based upon comparison against best-available satellite- and ground-based measurements. Moreover, C-LAMP has partnered with the U.S. Department of Energy's Program for Climate Model Diagnosis and Intercomparison (PCMDI) to collect, archive, and distribute—via the Earth System Grid (ESG)—model results from C-LAMP experiments performed by international modeling groups in the same fashion as was done for the model results used in the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4). In addition, because future IPCC Assessment Reports are expected to be based on results from integrated Earth System Models (ESMs), C-LAMP is helping to establish the metadata standards for model output from terrestrial biogeochemistry components of ESMs. Proposed as an extension to the netCDF Climate and Forecast (CF) 1.1 Convention, these metadata standards will facilitate future model-model and model-measurement intercomparisons. A prototype diagnostics tool has been developed for C-LAMP that summarizes model results, produces graphical representations of these results as compared with observational data sets, and scores models on their scientific performance.

Keywords: C-LAMP; model verification; model intercomparison; carbon cycle; terrestrial biogeochemistry

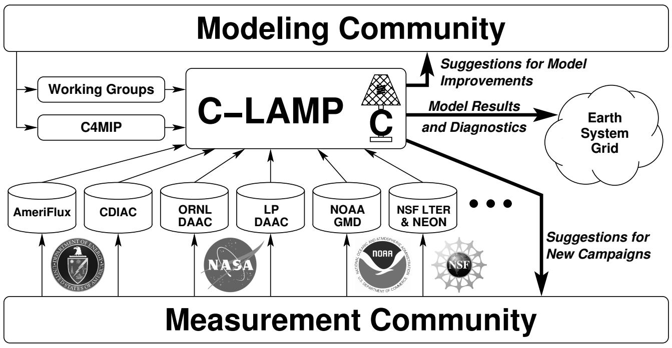

Figure 1: The Carbon-Land Model Intercomparison Project (C-LAMP) helps to bridge the gap between the measurement and modeling communities by comparing models against best-available observational data sets. C-LAMP provides feedback to both communities by offering suggestions for model improvements and by suggesting new measurement campaigns. All C-LAMP model results and diagnostics are distributed via the Earth System Grid (ESG).

1 INTRODUCTION

For the continued advance of climate change research it is particularly important for general circulation models (GCMs) to be extended to capture the global effects and feedbacks of carbon and other biogeochemical cycles. This need has resulted in new efforts to include atmospheric chemistry and land and ocean biogeochemistry into the next generation of climate models, now often referred to as Earth System Models (ESMs). While a number of terrestrial and ocean carbon models have been coupled to GCMs, recent work has shown that such models can yield a wide range of results [Friedlingstein et al., 2006]. This study suggests that a more rigorous set of offline and partially coupled experiments along with detailed analyses, including comparisons with measurements, are warranted.

The Carbon-Land Model Intercomparison Project (C-LAMP) provides a protocol and metrics for the intercomparison of terrestrial biogeochemistry models through a set of carefully crafted simulation experiments. Originally developed under the guise of the Community Climate System Model (CCSM) Biogeochemistry Working Group to test a number of such models within the CCSM3 framework [Hoffman et al., 2007], C-LAMP has been extended to include the larger international research community. Unlike traditional model intercomparisons, C-LAMP has established scientific model performance metrics based upon comparison against best-available satellite- and ground-based measurements. C-LAMP provides feedback to the modeling community by offering suggestions for model improvements and to the measurement community by suggesting new measurement campaigns. In addition, all model results will be made available through the Earth System Grid (ESG), the same system that distributed results used in the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4).

2 THE C-LAMP PROTOCOL

2.1 Experiment 1: Uncoupled Simulations

Experiment 1 consists of uncoupled simulations of the terrestrial carbon model specifically designed 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 carbon dioxide (CO_2), nitrogen (N) deposition, and land cover change on projections of terrestrial carbon fluxes during the 20th century. These simulations are forced using an improved NCEP/NCAR reanalysis meteorology data set from Qian et al. [2005] that covers the years 1948–2004. The prescribed global atmospheric CO_2 is from the C^4MIP reconstruction of Friedlingstein et al. [2006], extended out to the year 2005. A nitrogen deposition climatology is used for the pre-industrial simulations, while a time series is used starting in year 1890. Both of these data sets were developed as part of the SANTE FE project [Lamarque et al., 2005]. Historical global land cover data sets are those developed by Feddema et al. [2005] for climate change studies. The static land cover is that from the year 1798. Recently added were experiments designed to test the response of the models to a sudden increase in atmospheric CO_2 against the results from field measurements of the Free Air CO_2 Experiments (FACE) reported by Norby et al. [2005].

Initially, the protocol provided two equilibrium criteria for model spin up. These were 1) the absolute value of global land net ecosystem exchange (NEE) must be less than 0.05 PgC/y when taken as an average over a full 25-year repeat cycle of the meteorology drivers, and 2) the absolute value of NEE in every model grid cell must be less than 1.0 $gC/m^2/y$ when taken as an average over a full 25-year repeat cycle of the meteorology drivers. These criteria have proven to be too stringent; however, determining an adequate degree of equilibrium attainment is an open research question that is likely to be model dependent. Acceleration techniques are typically employed to reduce the simulation time required to reach an adequately spun up model state.

The Experiment 1 simulations are listed in Table 1. Experiments 1.1 and 1.2 are the spin up and control runs, respectively, and both cycle the first 25 years of the meteorology drivers with a fixed pre-industrial CO_2 concentration, climatological N deposition, and static land cover. Experiment 1.3 is initialized from year 1948 of the control run, and it uses the full meteorology time series to isolate the effect of varying only the climate. Experiment 1.4 begins in 1798 and includes the effects of varying climate, CO_2 concentration, and N deposition. Experiment 1.5 also begins in 1798 and adds the effects of historical land use change. Experiments 1.6 and 1.7 are the FACE control and transient simulations, respectively. They branch off Experiment 1.4, with static land cover, at year 1997 and extend out to year 2100, cycling the last 25 years of the meteorology drivers. Experiment 1.6 holds atmospheric CO_2 concentration and N deposition constant at year 2005 values, while Experiment 1.7 holds atmospheric CO_2 at 550 ppm, the nominal value from FACE.

2.2 Experiment 2: Partially Coupled Simulations

Experiment 2 consists of partially coupled simulations of the terrestrial carbon model with an active atmosphere model exchanging energy and moisture. In these experiments, atmospheric CO_2 is radiatively active and follows the prescribed historical trajectory used in Experiment 1. As in C^4MIP, the climate system is forced using sea surface temperatures (SSTs) and corresponding sea ice concentrations from the Hadley Centre for years 1875–2003, and extended to 2005 by Keith Lindsay. However, because of problems encountered in the Ocean Carbon Model Intercomparison Project (OCMIP) data set used in C^4MIP, prescribed ocean CO_2 fluxes come instead from an ocean simulation performed by Doney, *et al.* Fossil fuel emissions are annual estimates from the SRES A2 scenario, except in Experiment 2.6 where these emissions have been seasonalized to monthly values following the technique described by Erickson et al. [2008]. Because radiative CO_2 is prescribed, the CO_2 from land, ocean, and fossil fuel emissions are advected individually as inert tracers in the atmosphere.

The Experiment 2 simulations are listed in Table 2. Experiment 2.1 is the spin up run. It is initialized from the spun up state of Experiment 1.1, it cycles SSTs from years 1875–1899, and it uses a pre-industrial CO_2 forcing. Experiment 2.2 is the control simulation, run from 1800–2004, using the same forcing as Experiment 2.1. Experiment 2.3 also runs from 1800–2004, it adds the full time series of SSTs for years 1875–2004, and it employs the reconstructed time series for radiatively active CO_2 forcing. This experiment isolates the effects of changing only the climate. Experiment 2.4 is similar to Experiment 2.3, but it adds tracers for A2 fossil fuel emissions, ocean fluxes, and land NEE. In addition, a time series of atmospheric CO_2 concentration and N deposition forcing are applied to the land, so it includes the effects of varying climate, CO_2 concentrations, and N deposition. Experiment 2.5 adds the effects of historical land use change. Finally, Experiment 2.6 is like Experiment 2.4, but it uses seasonalized A2 fossil fuel emissions, instead of annual values, to demonstrate their effect on the seasonal cycle of atmospheric CO_2.

Table 1: The specifications for simulations contained in Experiment 1.

		NCEP/NCAR Forcing			**Land [CO_2]**				**N Deposition**			**Land Cover**	
Exp	**Time Period**	Cycling 1948–1972	Time Series	Cycling 1980–2004	Pre-Ind Constant	Time Series	2005 Time Series	FACE Constant	Clima-tology	Time Series	2005 Time Series	Constant	Time Series
1.1	As needed	✓			✓				✓			✓	
1.2	1798–2004	✓			✓				✓			✓	
1.3	1948–2004		✓		✓				✓			✓	
1.4	1798–1889	✓				✓			✓			✓	
	1890–1947	✓				✓				✓		✓	
	1948–2004		✓			✓				✓		✓	
1.5	1798–1889	✓				✓			✓				✓
	1890–1947	✓				✓				✓			✓
	1948–2004		✓			✓				✓			✓
1.6	1997–2100			✓			✓				✓	✓	
1.7	1997–2100			✓				✓			✓	✓	

Table 2: The specifications for simulations contained in Experiment 2.

		SST and Sea Ice		**Radiative [CO_2]**		**Fossil Fuel**			**Land [CO_2]**		**N Deposition**		**Land Cover**	
Exp	**Time Period**	Cycling 1875–1899	Time Series	Pre-Ind Constant	Time Series	A2	A2S	**Ocean CO_2 Fluxes**	Pre-Ind Constant	Time Series	Clima-tology	Time Series	Constant	Time Series
2.1	As needed	✓		✓					✓		✓		✓	
2.2	1800–2004	✓		✓					✓		✓		✓	
2.3	1800–1874	✓			✓				✓		✓		✓	
	1875–2004		✓		✓				✓		✓		✓	
2.4	1800–1874	✓			✓	✓		✓		✓	✓		✓	
	1875–1889		✓		✓	✓		✓		✓	✓		✓	
	1890–2004		✓		✓	✓		✓		✓		✓	✓	
2.5	1800–1874	✓			✓	✓		✓		✓	✓			✓
	1875–1889		✓		✓	✓		✓		✓	✓			✓
	1890–2004		✓		✓	✓		✓		✓		✓		✓
2.6	1800–1874	✓			✓		✓	✓		✓	✓		✓	
	1875–1889		✓		✓		✓	✓		✓	✓		✓	
	1890–2004		✓		✓		✓	✓		✓		✓	✓	

3 Performance Metrics

C-LAMP has established model performance metrics that employ comparison against best-available satellite-, aerial-, and ground-based measurements. These metrics will continue to evolve as new and improved observational data sets become available. The metrics are targeted at examining the sensitivity of biogeochemical fluxes and pools to changes in driver variables, rather than the absolute value of those fluxes and pools, recognizing that pools are poorly constrained by observations and that fluxes critically depend on these pools and the physical climate within the model. For example, measurements of net primary production (NPP) normalized by precipitation are compared to model results normalized in the same way, to adjust for possible atmospheric model biases in precipitation. Similarly, Pearson's r correlation coefficient is computed between satellite observations and model distributions of NPP and leaf area index (LAI), which provides a measure of the correspondence of the variability of these quantities instead of the correspondence of actual values.

A number of NPP metrics have been defined. First, NPP from control runs is compared with NPP from the Ecosystem Model-Data Intercomparison (EMDI) Class A observations at 81 sites. Here actual values from entire model grid cells are compared against site observations, and the scale mismatch can contribute to biases and errors in determining model performance. Scatter plots of observed vs. modeled NPP are produced as diagnostics. Second, NPP normalized by precipitation is compared between the same EMDI observations and model results. This reduces effects of biases in the atmospheric model's hydrological cycle, but in some areas, NPP is limited by temperature (or the length of the growing season) and not by precipitation. Diagnostic plots of NPP vs. mean annual precipitation are produced to support this evaluation. Third, Pearson's r correlation coefficient is computed between MODIS (Moderate Resolution Imaging Spectroradiometer) MOD17 annual net primary productivity from Zhao et al. [2005] and model results, both globally and zonally by latitude. The former tests the models' ability to capture observed spatial variability, while the latter is designed to identify possible extra-tropical or tropical biases in model performance. Maps of global annual NPP and latitudinal zonal mean plots are generated for this evaluation.

Three LAI metrics have been established: correspondence with the annual mean, maximum, and phase (*i.e.*, month of maximum LAI) from MODIS MOD17 by land/biome class. Again, Pearson's r correlation coefficients are computed between satellite and model distributions. It is recognized that satellite-derived estimates of LAI are strongly dependent on atmospheric and canopy radiative transfer models that require validation, and biases in observations are likely to impact model performance scores. Phase should be less sensitive to these types of potential biases. Maps of LAI annual mean, maximum, and phase from both the observations and the model results, as well as difference maps, are produced to support LAI evaluations.

Metrics for the seasonal cycle of atmospheric CO_2 test the combined effects of the seasonal timing and magnitude of NPP and heterotrophic respiration in northern hemisphere biomes. Good performance provides some confidence in the temperature sensitivity of respiration for those biomes in the model and suggests that prognostic leaf area, and thus gross primary production (GPP) and NPP, is being simulated correctly. The observations are obtained from the NOAA Globalview data set of measurements from surface stations. Correspondence in latitudinal zones as well as correlation and amplitude ratios at individual sites are tested as part of these metrics. Since ocean and fossil fuel fluxes contribute only weakly to the CO_2 seasonal cycle, it serves as a good diagnostic of biosphere-atmosphere exchange in northern hemisphere ecosystems. However, biosphere fluxes from the model require a model of atmospheric transport, and biases in the horizontal or vertical mixing in the transport model can influence performance for these metrics. Plots of monthly mean observations vs. model results for latitudinal zone and for individual stations are generated.

Measurements of carbon stocks are very limited, but a recent estimate of above-ground live biomass in the Amazon basin by Saatchi et al. [2007] provides one set of observations useful for comparison with model results. For this metric, both the total above-ground live biomass and its spatial pattern are compared between observations and model results. Maps of biomass from

Figure 2: The Earth System Grid (ESG).

observations and model results and difference maps are produced for this evaluation.

The wide deployment of eddy covariance flux towers offers the opportunity to constrain modeled fluxes of latent and sensible heat, net radiation, and CO_2 across a diversity of world biomes. Measurements from the Ameriflux sites are readily available, and these are used to evaluate model performance for latent heat, sensible heat, NEE, GPP, and ecosystem respiration (ER). Models are scored for correspondence with each of these factors across 74 sites. Plots containing measured and modeled results for each of these quantities for every site are generated.

Additional diagnostics of transient dynamics are produced to further characterize model behavior. These include calculations of turnover times for leaf, wood, fine root, litter, coarse woody debris, and soil carbon pools by biome type and tables of carbon stocks and fluxes meant to elucidate responses to El Niño phenomena. As additional observational data sets become available, they can be added to the C-LAMP diagnostics to improve its utility in evaluating performance of biosphere models.

4 The Earth System Grid (ESG)

The model output from the C-LAMP experiments will be made available to the wider international research community through the Earth System Grid Center for Enabling Technologies (ESG-CET) [Ananthakrishnan et al., 2007]. 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 [Bernholdt et al., 2005] Two ESG Portals have been established, and a new one has been deployed at ORNL to support C-LAMP (see Figure 2). 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, ESG was the primary means for distribution of IPCC data that resulted in over 300 scientific publications supporting AR4 [IPCC, 2007].

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. In particular, proposals are being developed to extend the netCDF Climate and Forecast (CF) metadata conventions [Eaton et al., 2008] to include better representation of common biosphere model output fields.

5 Conclusions

The C-LAMP experiments provide a means for rigorous testing and intercomparison of terrestrial biogeochemistry models. A growing number of C-LAMP metrics can be used to suggest where, when, and why such models exhibit deficiencies. Tracking changing scores offers a quantitative means for measuring model improvements. A diagnostics tool has been developed that summarizes model results, produces graphical representations of the model results as compared with observational data sets, and automatically scores models based on their scientific performance. This tool may be extended in the future to provide a user-friendly method for modelers to test and score their own model results prior to contributing them to ESG. C-LAMP is an open, community project that benefits from the suggestions and input of community researchers. More information about C-LAMP, the experimental protocol, model performance metrics, and early results from participating models is available at http://www.climatemodeling.org/c-lamp.

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