Systematic Assessment of Terrestrial Biogeochemistry in Coupled Climate–Carbon Models

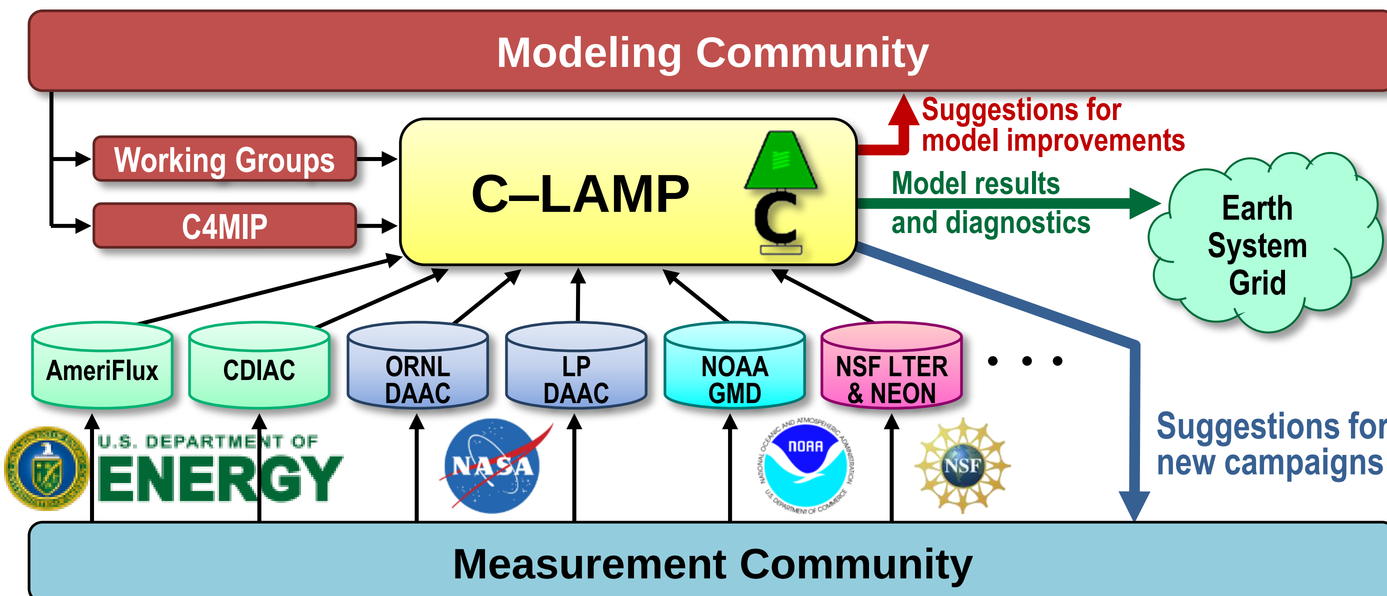
Presented by

Forrest M. Hoffman[1], James T. Randerson[2], Peter E. Thornton[1], Natalie M. Mahowald[3], Keith Lindsay[4], Yen-Huei Lee[4], Cynthia D. Nevison[4], Scott C. Doney[5], Gordon B. Bonan[4], Reto Stöckli[6], Curtis C. Covey[7], Steven W. Running[8], and Inez Y. Fung[9]

[1]Oak Ridge National Laboratory, [2]University of California–Irvine, [3]Cornell University, [4]National Center for Atmospheric Research, [5]Wood Hole Oceanographic Institute, [6]MeteoSwiss, [7]Lawrence Livermore National Laboratory, [8]University of Montana, and [9]University of California–Berkeley

What is C-LAMP?

- The Carbon-Land Model Intercomparison Project (C-LAMP) began as a CCSM Biogeochemistry Working Group project to assess model capabilities in the coupled climate system and to explore processes important for inclusion in the CCSM4 Earth System Model for use in the IPCC Fifth Assessment Report (AR5)
- Unlike traditional MIPs, C-LAMP was designed to confront models with best-available observational datasets, develop metrics for evaluation of biosphere models, and build a general-purpose biogeochemistry diagnostics package for model evaluation



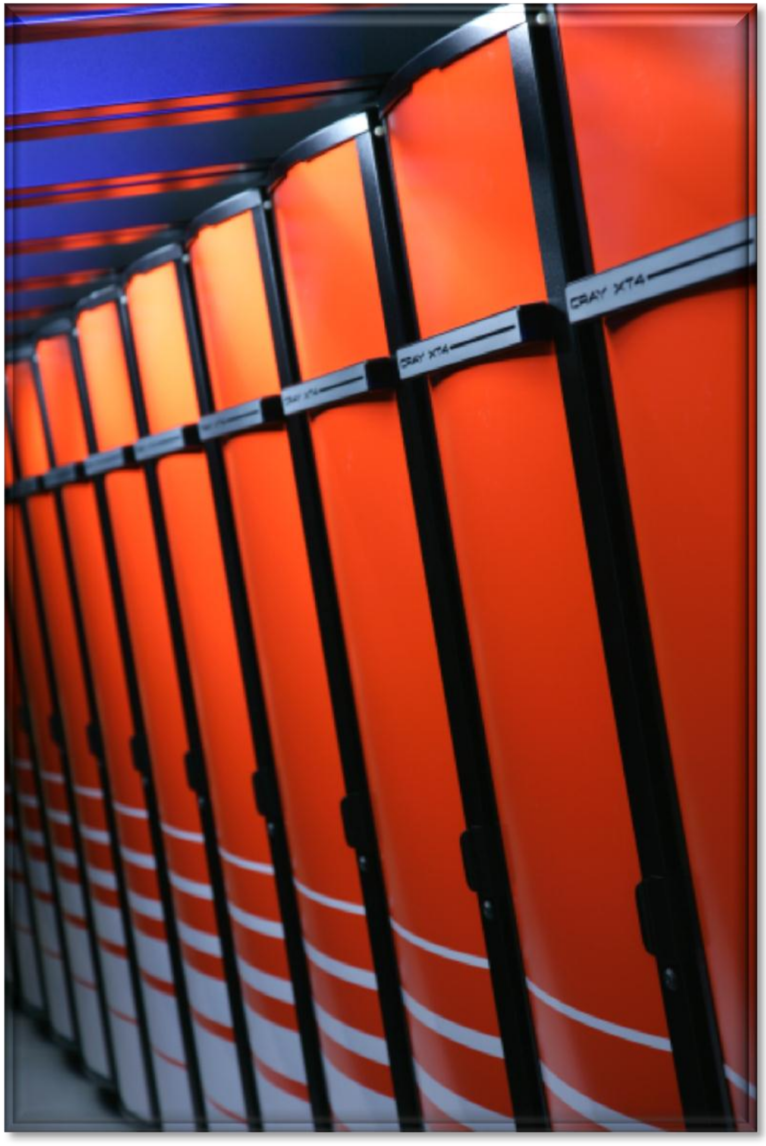
Computational Climate Science End Station

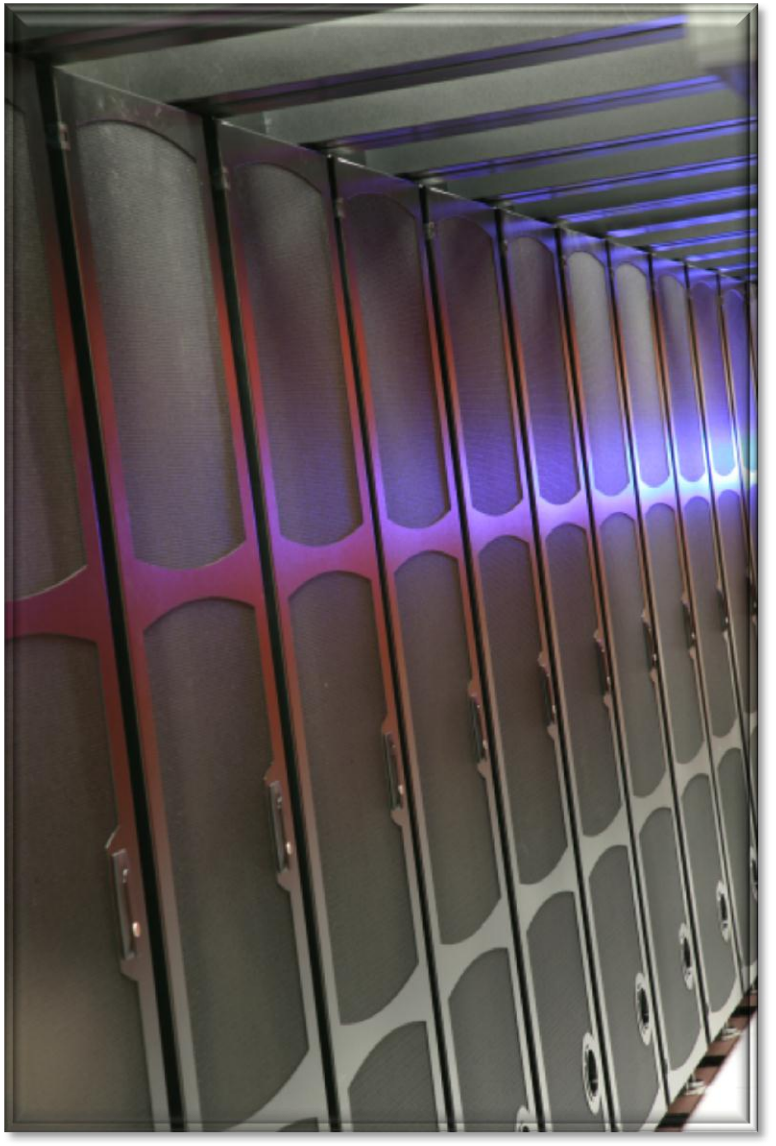
- **C-LAMP is a Biogeochemistry Subproject of the Computational Climate Science End Station (Warren Washington, PI), a U.S. Department of Energy INCITE Project**
- **Models were initially run on the Cray X1E vector supercomputer in ORNL's National Center for Computational Sciences (NCCS)**

1024 processors (MSPs), 2048 GB memory, and 18.08 Tflop/s peak

— DECOMMISSIONED September 30, 2008 —

XT4 Jaguar: 250 Tflop/s





XT5 Jaguar: 1.059 Pflop/s

Model configurations

- Biosphere models coupled to the Community Climate System Model version 3.1
  - CLM3-CASA´—Carnegie/Ames/Stanford Approach Model previously run in CSM1.4 (Fung)
  - CLM3-CN—coupled carbon and nitrogen cycles based on the Biome-BGC model (Thornton)
  - LSX-IBIS—Integrated Biosphere Simulator from U. Wisconsin previously run in PCTM (Thompson)
- Because LSX-IBIS is not coupled to the CLM3 biophysics and was not a candidate for inclusion in CCSM4, only CLM3-CASA´ and CLM3-CN were evaluated in C-LAMP
- CCSM3.1 partially coupled ("I" & "F" configurations) run at T42 resolution (~2.8° × 2.8°), spectral Eulerian dycore, 1° × 0.27°–0.53° ocean and sea ice data models (T42gx1v3)

C-LAMP protocol overview

- Experiment 1: Models forced with an improved NCEP/NCAR reanalysis climate data set (Qian et al. 2006) to examine the influence of climate variability, prescribed atmospheric CO_2, and land cover change on terrestrial carbon fluxes during the 20th century (specifically 1948–2004)
- Experiment 2: Models coupled with an active atmosphere (CAM3), prescribed atmospheric CO_2, prescribed sea surface temperatures and ocean carbon fluxes to examine the effect of a coupled biosphere-atmosphere for carbon fluxes and climate during the 20th century
- All the forcing and observational datasets are being shared, and model results are available through the Earth System Grid (ESG), just like for CMIP3 (the IPCC AR4 model results)
- Experimental protocol, output fields, and metrics are available at http://www.climatemodeling.org/c-lamp/

C–LAMP simulation protocol

Offline Forcing with NCEP/NCAR Reanalysis Description

Exp	Description	Time period
1.1	Spin up	~4,000 y
1.2	Control	1798–2004
1.3	Varying climate	1948–2004
1.4	Varying climate, CO_2, and N deposition	1798–2004
1.5	Varying climate, CO_2, N deposition, and land use	1798–2004
1.6	Free Air CO_2 Enrichment (FACE) control	1997–2100
1.7	Free Air CO_2 Enrichment (FACE) transient	1997–2100

Coupled Land-Atmosphere Forcing with Hadley SSTs

Exp	Description	Time period
2.1	Spin up	~2,600 y
2.2	Control	1800–2004
2.3	Varying climate	1800–2004
2.4	Varying climate, CO_2, and N deposition	1800–2004
2.5	Varying climate, CO_2, N deposition, and land use	1800–2004
2.6	Varying climate, CO_2, N deposition, and seasonal FFE	1800–2004

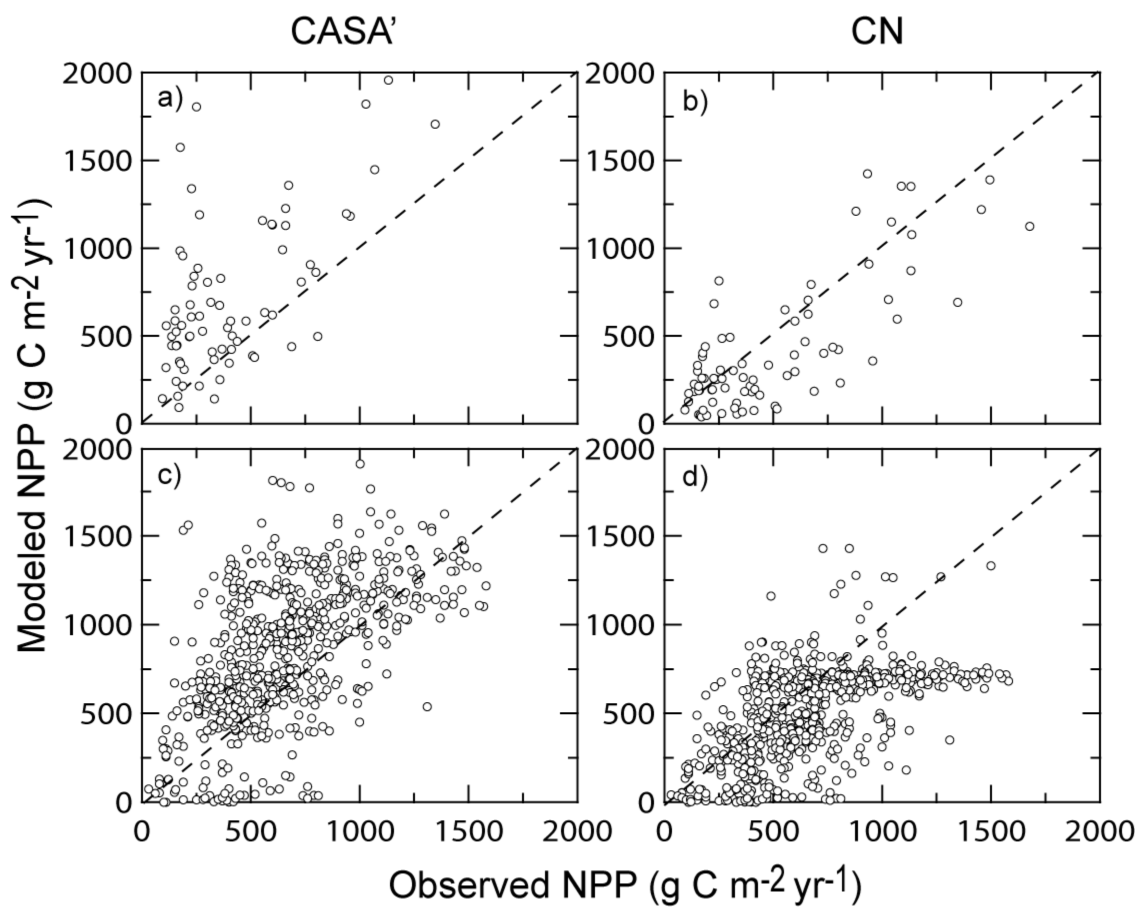
All but the land use experiments were run with CCSM3.1 using CLM3-CASA´ and CLM3-CN biogeochemistry models yielding >16,000 y and ~50 TB

C-LAMP performance metrics and diagnostics

- An evolving document on metrics for model evaluation is available at http://www.climatemodeling.org/c-lamp/
- Each model is scored with respect to its performance on various output fields compared with best-available observational datasets
- Examples include
  - Leaf area index (LAI): comparison of phase and spatial distribution using MODIS
  - Net primary production (NPP): comparison with EMDI and correlation with MODIS
  - CO_2 seasonal cycle: comparison with NOAA/Globalview flask sites after combining fluxes with impulse response functions from TRANSCOM
  - Regional carbon stocks (Saatchi et al. 2006, Batjes 2006)
  - Carbon and energy fluxes (Fluxnet sites)
  - Other transient dynamics: β factor, fire emissions

Comparison with EMDI NPP

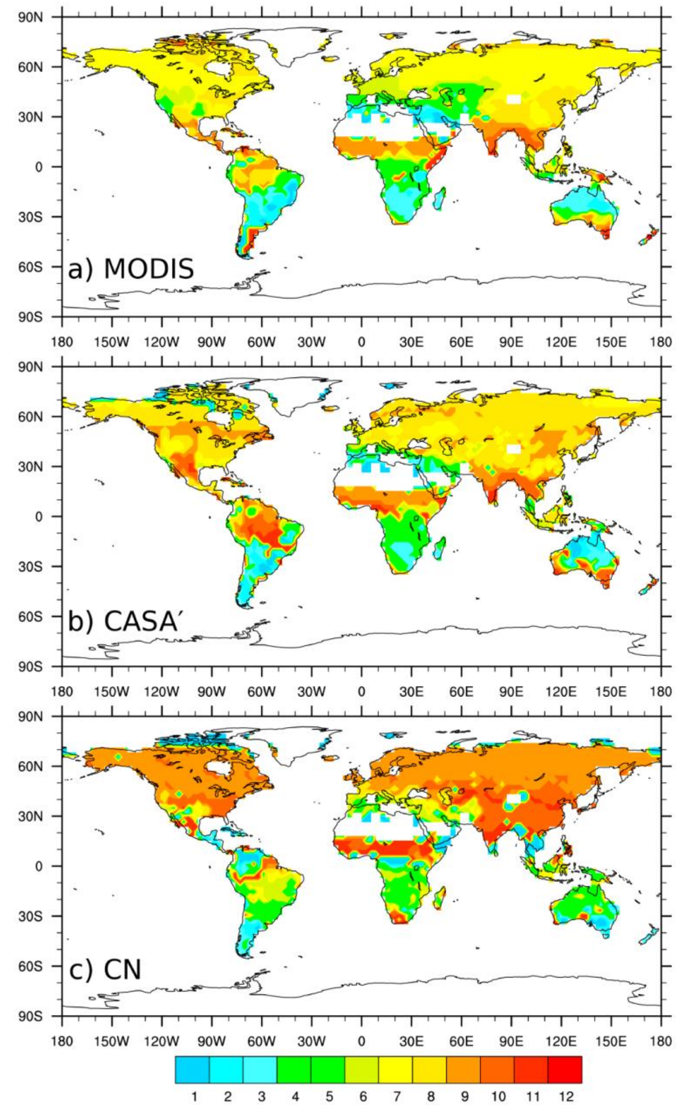
- Comparisons with field observations include net primary production (NPP) from the Ecosystem Model-Data Intercomparison (EMDI)
- Measurements were performed in different ways, at different times, and by different groups for a limited number of field sites
- Shown here are comparisons of NPP with EMDI Class A observations (Figures a and b) and Class B observations (Figures c and d)



Data provided by NASA Distributed Active Archive Center (DAAC) at ORNL

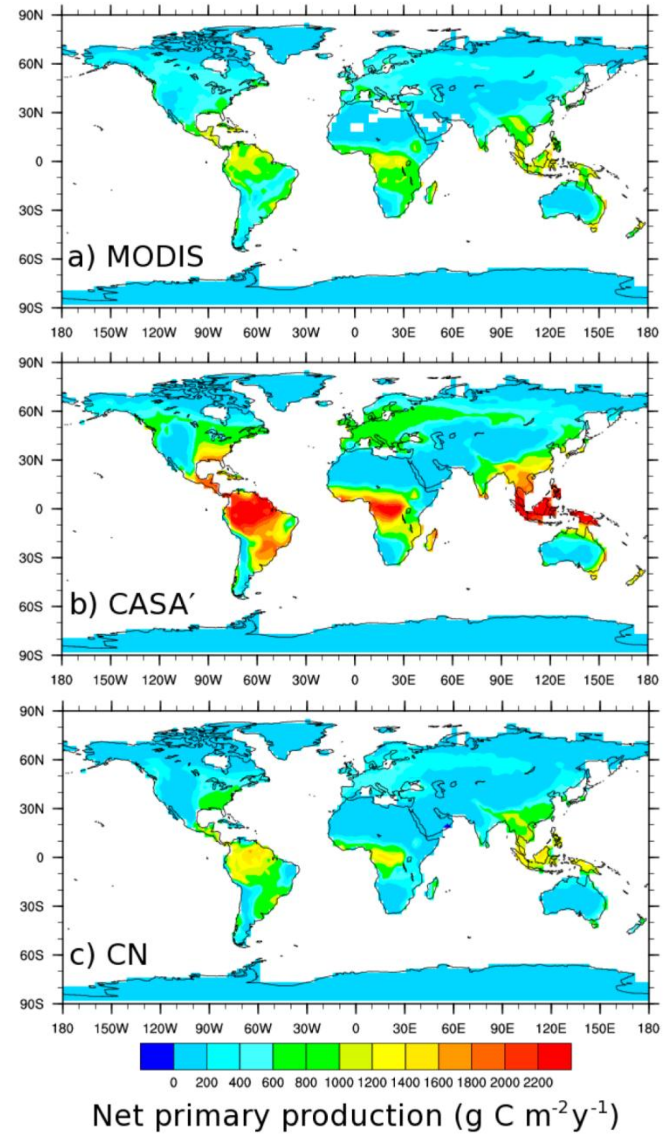
Comparison with MODIS LAI

- **Comparisons with satellite "modeled observations" must be made carefully because of high uncertainty**
- **This comparison with MODIS leaf area index (LAI) focuses on the month of maximum LAI (phase), a measurement with less uncertainty than the "observed" LAI values**
- **C-LAMP accounts for this uncertainty by weighting scores accordingly**
- **CLM-CASA´ scored 5.1/6.0 while CLM-CN scored 4.2/6.0 for this metric**



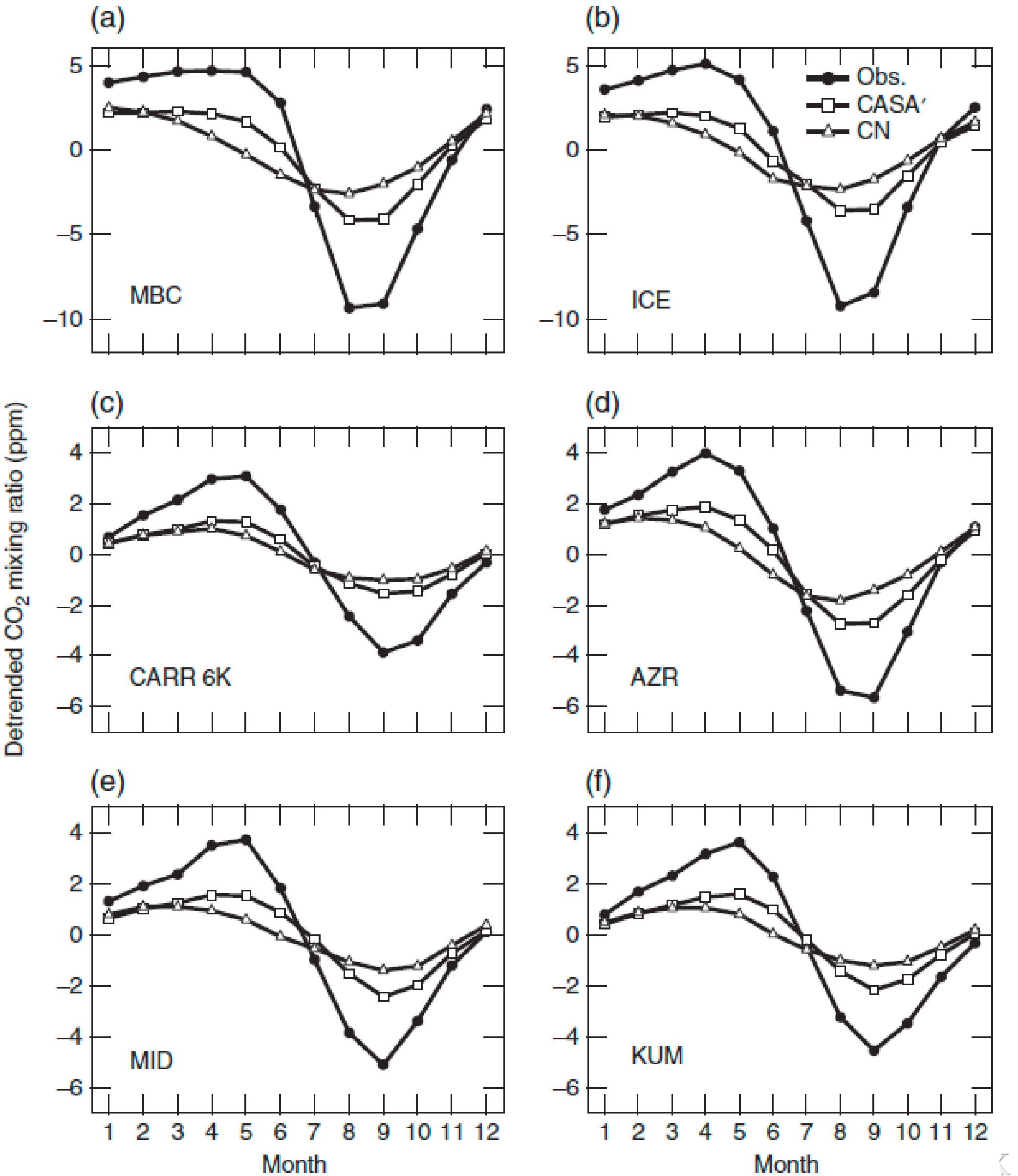
Comparison with MODIS NPP

- **MODIS net primary production (NPP) “observations” have higher uncertainty**
- **Comparison with MODIS NPP focuses on correlation of spatial patterns**
- **CLM-CASA´ scored 1.6/2.0 while CLM-CN scored 1.4/2.0**



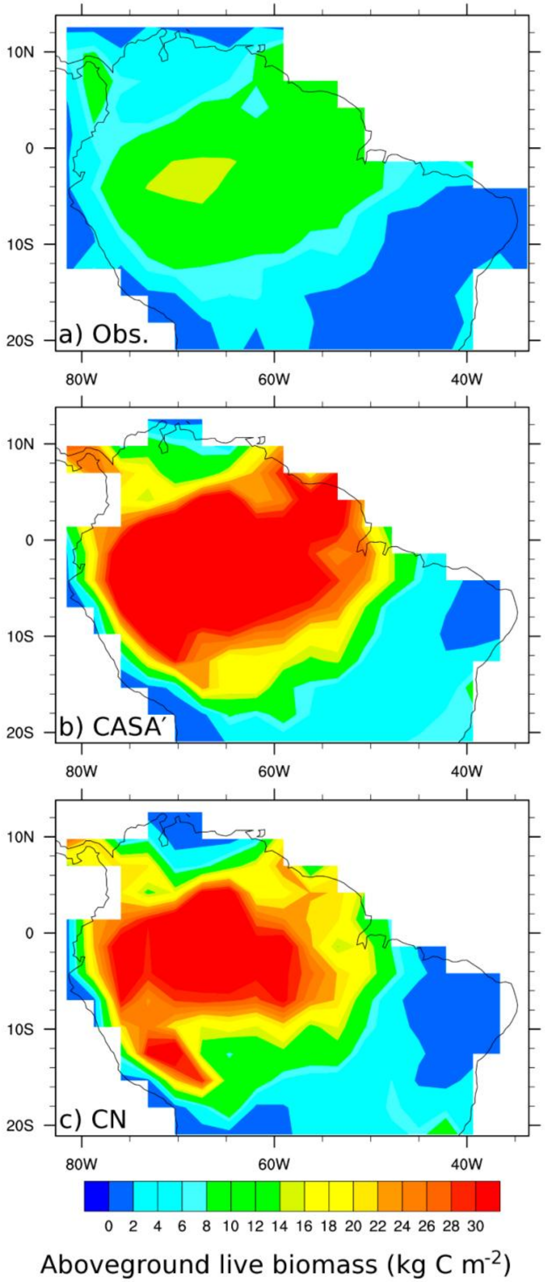
Seasonal cycle comparisons

- Comparisons with Globalview flask sites are made by combining model fluxes with impulse response functions from TRANSCOM
- Shown are the annual cycles of atmospheric CO_2 at
  (a) Mould Bay, Canada (76°N)
  (b) Storhofdi, Iceland (63°N)
  (c) Carr, Colorado (41°N)
  (d) Azores Islands (39°N)
  (e) Sand Island, Midway (28°N)
  (f) Kumakahi, Hawaii (20°N)
- CLM-CASA´ scored 10.4/15.0 while CLM-CN scored 7.7/15.0 for this metric



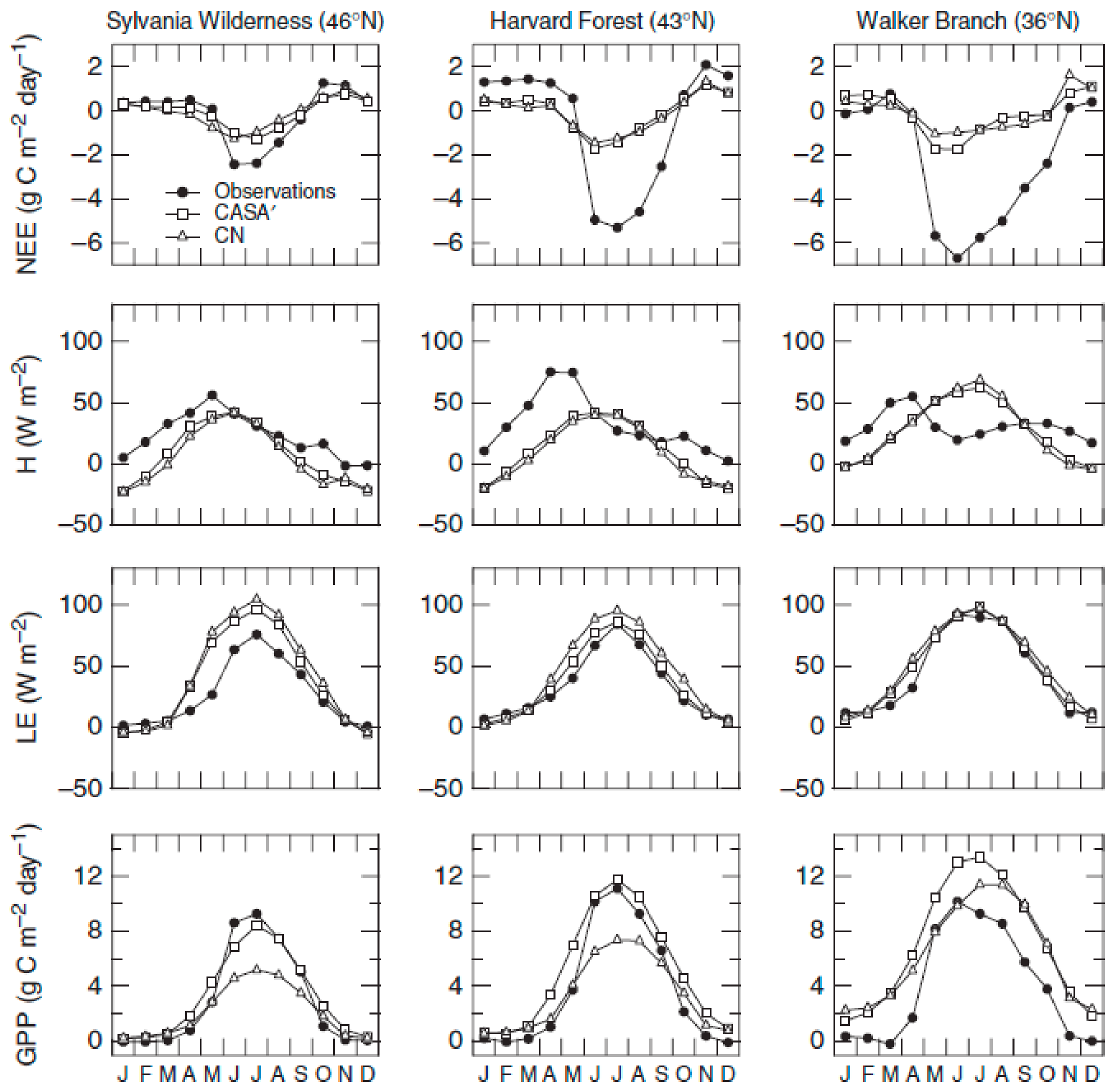
Comparison of carbon stock estimates

- Estimates of carbon stocks are very difficult to obtain
- This comparison with estimates of aboveground live biomass in the Amazon by Saatchi et al. (2006) shows that both models are too high by about a factor of 2
- Using a score based on normalized cell-by-cell differences, CLM-CASA′ scored 5.3/10.0 while CLM-CN scored 5.0/10.0



Comparison with AmeriFlux sites

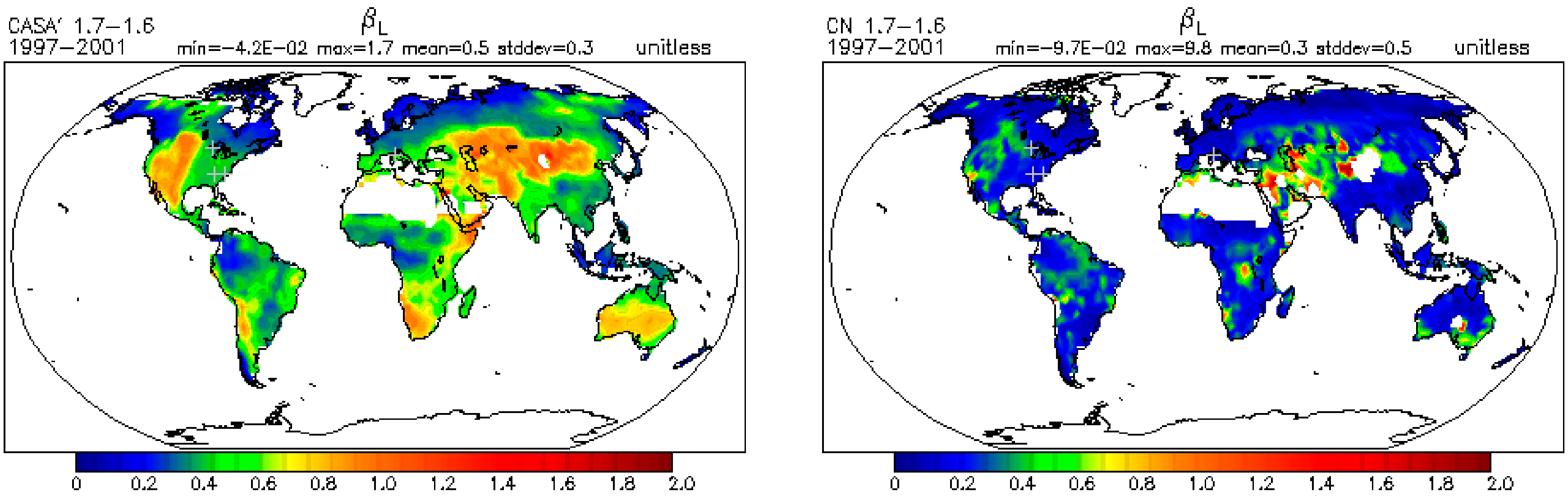
- Comparisons with AmeriFlux eddy correlation CO_2 flux tower sites include net ecosystem exchange (NEE), gross primary production (GPP), respiration, shortwave incoming radiation, and latent and sensible heat
- Shown here is a comparison of model estimates with eddy covariance measurements from Sylvania Wilderness, Harvard Forest, and Walker Branch
- The Level 4 data were used for these analyses



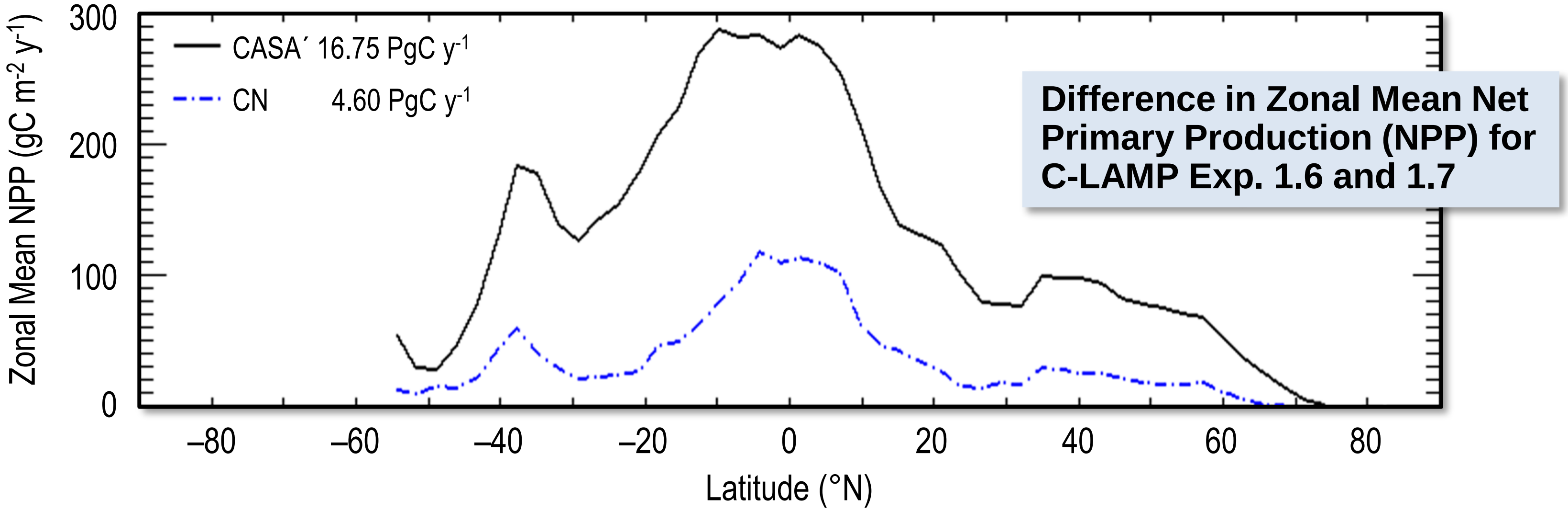
Data provided by ORNL Carbon Dioxide Information Analysis Center (CDIAC)

Comparison with FACE sites

- Additional field measurement comparisons include the Free Air CO_2 Enrichment (FACE) results, including the ORNL site
- The Norby et al. (2005) synthesis of four FACE site observations suggested "response of forest NPP to elevated [CO_2] is highly conserved across a broad range of productivity, with a stimulation at the median of 23 ± 2%"
- A C-LAMP experiment was added to test this result by increasing [CO_2] to 550 ppmv in 1997



FACE site comparison scores



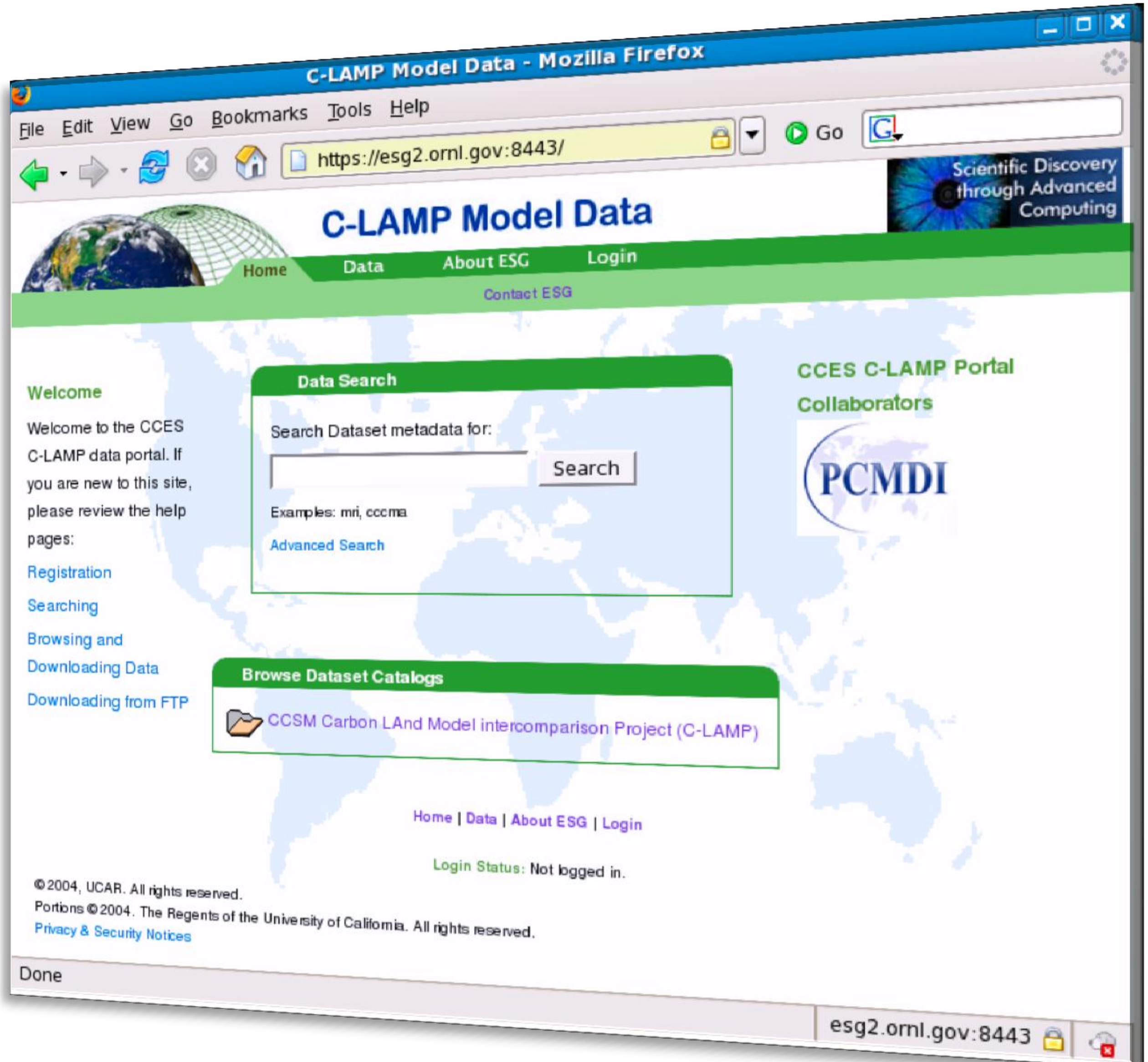
Site Name	Lon (°E)	Lat (°N)	Observations		CASA´			CN		
			NPP↑	β_L	NPP↑	β_L	Score	NPP↑	β_L	Score
Duke	-79.08	35.97	28.0%	0.69	16.4%	0.41	0.26	6.2%	0.15	0.65
Aspen	-89.62	45.67	35.2%	0.87	15.6%	0.39	0.39	12.4%	0.31	0.48
ORNL	-84.33	35.90	23.9%	0.59	17.3%	0.43	0.16	5.2%	0.13	0.64
POP-Euro	11.80	42.37	21.8%	0.54	20.0%	0.49	0.04	5.7%	0.14	0.59
4 site mean			**27.2%**	**0.67**	**17.3%**	**0.43**		**7.4%**	**0.18**	
Total M Score							**0.79**			**0.41**

But! Norby is now reporting reduced NPP enhancement at the ORNL FACE site due probably to N limitation!

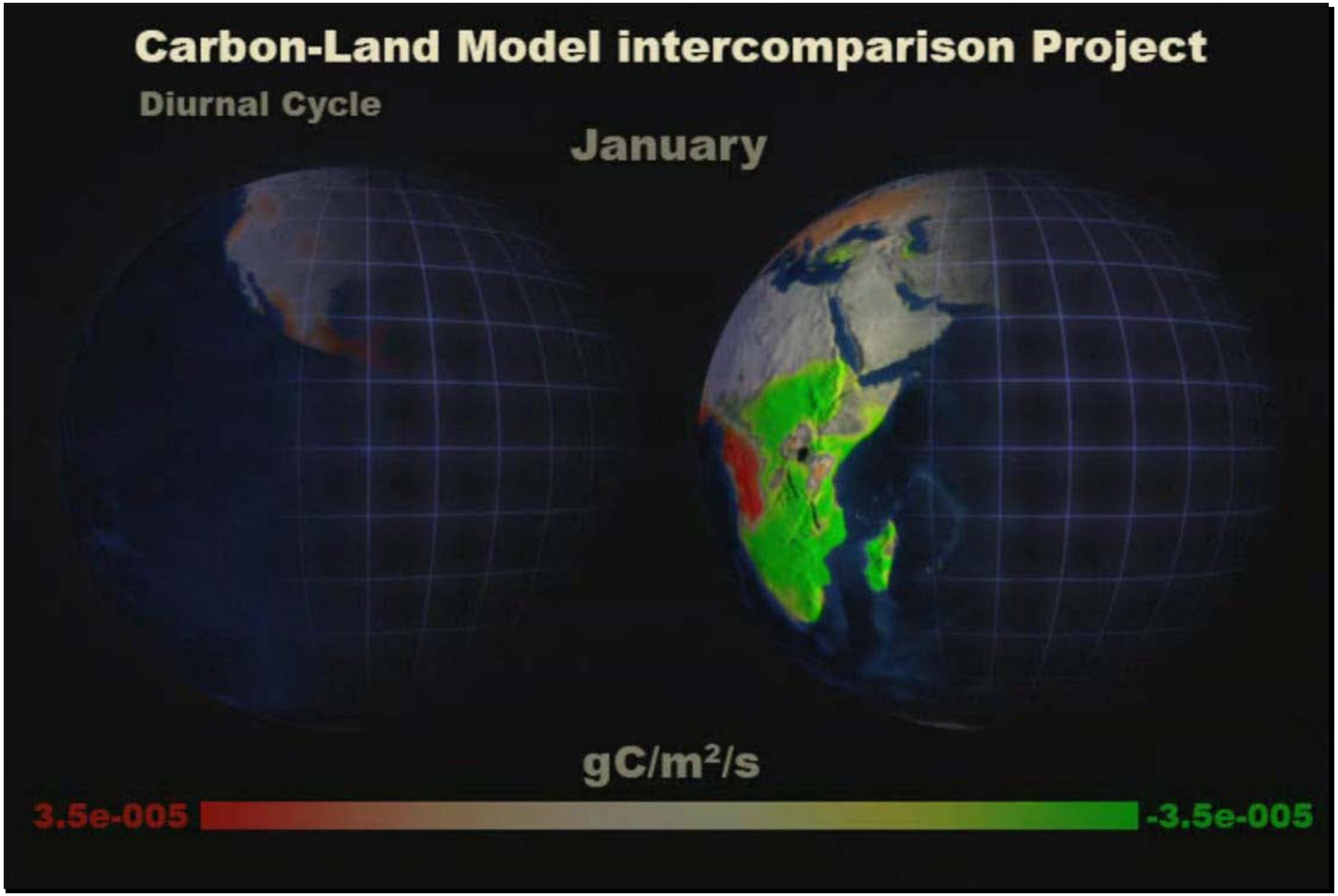
C-LAMP score sheet for CLM3-CASA′ and CLM3-CN

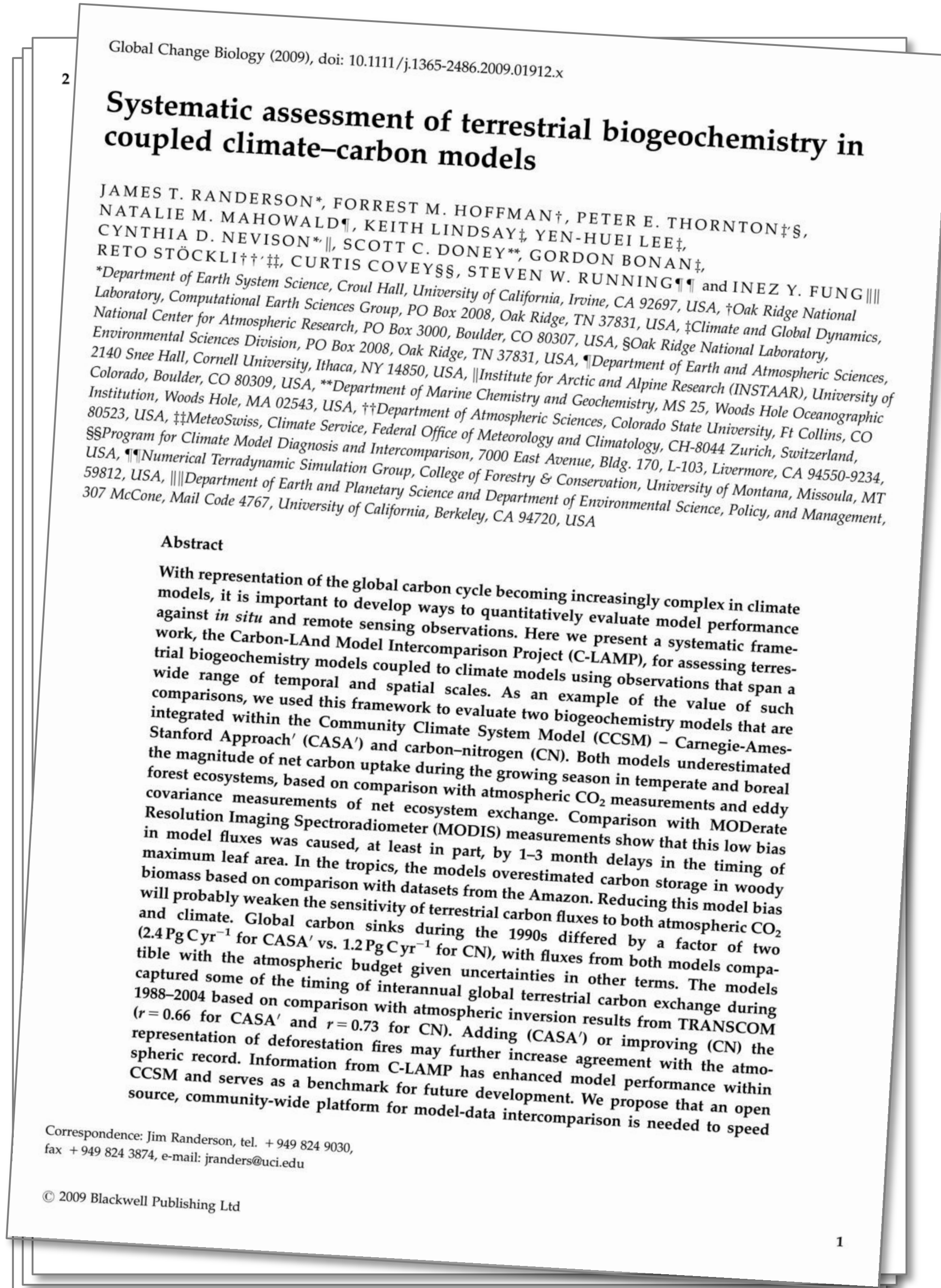
Metric	Metric components	Uncertainty of obs.	Scaling mismatch	Total score	Sub-score	CASA'	CN
LAI	**Matching MODIS observations**			**15.0**		**13.5**	**12.0**
	• Phase (assessed using the month of maximum LAI)	Low	Low		6.0	5.1	4.2
	• Maximum (derived separately for major biome classes)	Moderate	Low		5.0	4.6	4.3
	• Mean (derived separately for major biome classes)	Moderate	Low		4.0	3.8	3.5
NPP	**Comparisons with field observations and satellite products**			**10.0**		**8.0**	**8.2**
	• Matching EMDI Net Primary Production observations	High	High		2.0	1.5	1.6
	• EMDI comparison, normalized by precipitation	Moderate	Moderate		4.0	3.0	3.4
	• Correlation with MODIS (r^2)	High	Low		2.0	1.6	1.4
	• Latitudinal profile comparison with MODIS (r^2)	High	Low		2.0	1.9	1.8
CO_2 annual cycle	**Matching phase and amplitude at Globalview flask sites**			**15.0**		**10.4**	**7.7**
	• 60°–90°N	Low	Low		6.0	4.1	2.8
	• 30°–60°N	Low	Low		6.0	4.2	3.2
	• 0°–30°N	Moderate	Low		3.0	2.1	1.7
Energy and CO_2 fluxes	**Matching eddy covariance monthly mean observations**			**30.0**		**17.2**	**16.6**
	• Net ecosystem exchange	Low	High		6.0	2.5	2.1
	• Gross primary production	Moderate	Moderate		6.0	3.4	3.5
	• Latent heat	Low	Moderate		9.0	6.4	6.4
	• Sensible heat	Low	Moderate		9.0	4.9	4.6
Transient dynamics	**Evaluating model processes that regulate carbon exchange on decadal to century timescales**			**30.0**		**16.8**	**13.8**
	• Aboveground live biomass within the Amazon Basin	Moderate	Moderate		10.0	5.3	5.0
	• Sensitivity of NPP to elevated levels of CO_2: comparison to temperate forest FACE sites	Low	Moderate		10.0	7.9	4.1
	• Interannual variability of global carbon fluxes: comparison with TRANSCOM	High	Low		5.0	3.6	3.0
	• Regional and global fire emissions: comparison to GFEDv2	High	Low		5.0	0.0	1.7
			Total	**100.0**		**65.9**	**58.3**

Earth System Grid (ESG) node at ORNL for C-LAMP



Animation of hourly net ecosystem exchange





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JAMES T. RANDERSON*, FORREST M. HOFFMAN†, PETER E. THORNTON‡,§, NATALIE M. MAHOWALD¶, KEITH LINDSAY‡, YEN-HUEI LEE‡, CYNTHIA D. NEVISON*,||, SCOTT C. DONEY**, GORDON BONAN‡, RETO STÖCKLI††,‡‡, CURTIS COVEY§§, STEVEN W. RUNNING¶¶ and INEZ Y. FUNG|||

*Department of Earth System Science, Croul Hall, University of California, Irvine, CA 92697, USA, †Oak Ridge National Laboratory, Computational Earth Sciences Group, PO Box 2008, Oak Ridge, TN 37831, USA, ‡Climate and Global Dynamics, National Center for Atmospheric Research, PO Box 3000, Boulder, CO 80307, USA, §Oak Ridge National Laboratory, Environmental Sciences Division, PO Box 2008, Oak Ridge, TN 37831, USA, ¶Department of Earth and Atmospheric Sciences, 2140 Snee Hall, Cornell University, Ithaca, NY 14850, USA, ||Institute for Arctic and Alpine Research (INSTAAR), University of Colorado, Boulder, CO 80309, USA, **Department of Marine Chemistry and Geochemistry, MS 25, Woods Hole Oceanographic Institution, Woods Hole, MA 02543, USA, ††Department of Atmospheric Sciences, Colorado State University, Ft Collins, CO 80523, USA, ‡‡MeteoSwiss, Climate Service, Federal Office of Meteorology and Climatology, CH-8044 Zurich, Switzerland, §§Program for Climate Model Diagnosis and Intercomparison, 7000 East Avenue, Bldg. 170, L-103, Livermore, CA 94550-9234, USA, ¶¶Numerical Terradynamic Simulation Group, College of Forestry & Conservation, University of Montana, Missoula, MT 59812, USA, |||Department of Earth and Planetary Science and Department of Environmental Science, Policy, and Management, 307 McCone, Mail Code 4767, University of California, Berkeley, CA 94720, USA

Abstract

With representation of the global carbon cycle becoming increasingly complex in climate models, it is important to develop ways to quantitatively evaluate model performance against *in situ* and remote sensing observations. Here we present a systematic framework, the Carbon-LAnd Model Intercomparison Project (C-LAMP), for assessing terrestrial biogeochemistry models coupled to climate models using observations that span a wide range of temporal and spatial scales. As an example of the value of such comparisons, we used this framework to evaluate two biogeochemistry models that are integrated within the Community Climate System Model (CCSM) – Carnegie-Ames-Stanford Approach′ (CASA′) and carbon–nitrogen (CN). Both models underestimated the magnitude of net carbon uptake during the growing season in temperate and boreal forest ecosystems, based on comparison with atmospheric CO_2 measurements and eddy covariance measurements of net ecosystem exchange. Comparison with MODerate Resolution Imaging Spectroradiometer (MODIS) measurements show that this low bias in model fluxes was caused, at least in part, by 1–3 month delays in the timing of maximum leaf area. In the tropics, the models overestimated carbon storage in woody biomass based on comparison with datasets from the Amazon. Reducing this model bias will probably weaken the sensitivity of terrestrial carbon fluxes to both atmospheric CO_2 and climate. Global carbon sinks during the 1990s differed by a factor of two ($2.4\,Pg\,C\,yr^{-1}$ for CASA′ vs. $1.2\,Pg\,C\,yr^{-1}$ for CN), with fluxes from both models compatible with the atmospheric budget given uncertainties in other terms. The models captured some of the timing of interannual global terrestrial carbon exchange during 1988–2004 based on comparison with atmospheric inversion results from TRANSCOM ($r = 0.66$ for CASA′ and $r = 0.73$ for CN). Adding (CASA′) or improving (CN) the representation of deforestation fires may further increase agreement with the atmospheric record. Information from C-LAMP has enhanced model performance within CCSM and serves as a benchmark for future development. We propose that an open source, community-wide platform for model-data intercomparison is needed to speed

Correspondence: Jim Randerson, tel. +949 824 9030, fax +949 824 3874, e-mail: jranders@uci.edu

1

Recent progress and future work

- C-LAMP helped drive the development of model improvements in the terrestrial biogeochemistry models for the Community Land Model version 4 (CLM4)
- Subsequent C-LAMP analyses of six model configurations using CLM3.6 (a pre-release version of CLM4) with CASA´ and CN demonstrated much improved performance by CN
- It is now recognized that physical model changes must be tested using C-LAMP to ensure that these changes do not have negative impacts on biogeochemistry model performance
- **Next:** N-LAMP—develop a strategy for benchmarking the nitrogen cycle in land surface models

Contact

Forrest Hoffman

Oak Ridge National Laboratory
(865) 576-7680
forrest@climatemodeling.org