An International Land-Biosphere Model Benchmarking Activity for the IPCC Fifth Assessment Report (AR5)

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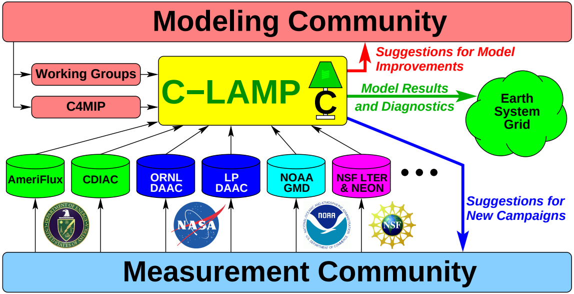
- The **Carbon-Land Model Intercomparison Project (C-LAMP)** began as a CCSM Biogeochemistry Working Group project to assess model capabilities in the coupled climate system and to explore processes important for inclusion in the CCSM4 Earth System Model for use in the IPCC Fifth Assessment Report (AR5).
- 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.



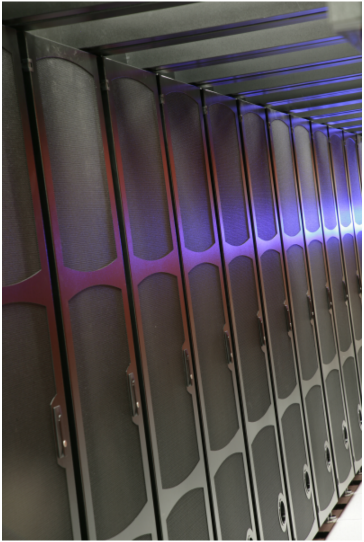
- C-LAMP is a Biogeochemistry Subproject of the **Computational Climate Science End Station** (Warren Washington, PI), a U.S. Dept. of Energy INCITE Project.
- Models were initially run on the Cray X1E vector supercomputer in ORNL's **National Center for Computational Sciences (NCCS)**.

Cray X1E (phoenix)

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

DECOMMISSIONED September 30, 2008

XT4 Jaguar: 250 TFlop/s



XT5 Jaguar: Fastest in the World at 1.759 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 ($\sim 2.8^\circ \times 2.8^\circ$), spectral Eulerian dycore, $1^\circ \times 0.27^\circ$–$0.53^\circ$ ocean & 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/

Offline Forcing with NCEP/NCAR Reanalysis		
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, 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 Common Model Output - Mozilla Firefox

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http://www.climatemodeling.org/c-lamp/protocol/model_output.php

C-LAMP Common Model Output

While all models participating in the Carbon Land Model intercomparison Project (C-LAMP) will output their own "native" fields, a common set of fields is needed to facilitate head-to-head comparison of the models to each other and to available observational datasets. Model results transmitted to the Earth System Grid for redistribution to the community will use common field names, netCDF long names, CF Standard Names and units. Contained below is a table of the common output fields required for the C-LAMP and consistent with the metadata conventions used for CMIP3, formerly called the IPCC 4th Assessment Model Output database. Corrections and suggestions are solicited on this information. Software is available for rewriting model output into netCDF files following the Climate and Forecast (CF) Metadata Convention.

Version 2.1 - Aug 30, 2008

Atmospheric forcing

Variable Name	Long Name and CF Standard Name	Units	Comment	Statistics
husf	Specific humidity at atmospheric forcing height specific_humidity‡	kg kg-1		MHM, MHS, MM
prra	Rainfall precipitation flux rainfall_flux‡	kg m-2 s-1	Rainfall includes all liquid types (rain, large-scale, convective, etc.)	MHM, MHS, MM
prsn†	Snowfall precipitation flux snowfall_flux‡	kg m-2 s-1	Snowfall includes all frozen types (snow, hail, ice, etc.)	MHM, MHS, MM

Biogeochemistry

Variable Name	Long Name and CF Standard Name	Units	Comment	Statistics
agbc*	Above-ground biomass carbon above_ground_biomass_carbon_content	kg m-2	Total carbon content in above-ground live and dead carbon pool(s)	MM
aglbc*	Above-ground live biomass carbon above_ground_live_biomass_carbon_content	kg m-2	Total carbon content in above-ground live carbon pool(s)	MM
agnpp	Above-ground net primary production above_ground_net_primary_productivity_of_carbon	kg m-2 s-1	Component of net primary production attributable to above-ground live biomass	MM
ar	Autotrophic respiration autotrophic_respiration_of_carbon alias(es): plant_respiration_carbon_flux	kg m-2 s-1	Sum of maintenance respiration and growth respiration of vegetation	MHM, MHS, MM
bco	Biogenic carbon monoxide flux biogenic_carbon_monoxide_flux	kg m-2 s-1	Total biogenic carbon monoxide flux out of biosphere	MM

Done

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

Score Sheet for CLAMP - Mozilla Firefox

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http://www.climatemodeling.org/c-lamp/results/diagnostics/CN_vs_C/

C-LAMP Score Sheet for Biogeochemical Model Evaluation

Metric	Metric components	Observations & comparison protocol	Model CASA'	Model CN	Score (points)		
					Possible	CASA'	CN
LAI	MODIS Phase	global map	global map model vs obs	global map model vs obs	6.00	5.11	4.24
	MODIS Maximum	global map	global map model vs obs	global map model vs obs	5.00	4.60	4.26
	MODIS Mean	land class obs land class model global map	model vs obs table global map model vs obs	model vs obs table global map model vs obs	4.00	3.75	3.53
NPP	EMDI NPP observations	Class A table	table scatter plot	table scatter plot	1.00	0.68	0.73
		Class B table	table scatter plot	table scatter plot	1.00	0.83	0.82
	EMDI NPP normalized by PPT	Class A histogram	Class A histogram	Class A histogram	2.00	1.50	1.74
		Class B histogram	Class B histogram	Class B histogram	2.00	1.51	1.65
	Correlation with MODIS	global map	model map model vs obs	model map model vs obs	2.00	1.64	1.44
	Correlation with MODIS-zonal mean	zonal mean obs	zonal mean model vs obs plot	zonal mean model vs obs plot	2.00	1.88	1.84
CO_2 Seasonal Cycle — Comparison with Globalview phase and amplitude	60°N–90°N	—	—	—	6.00	4.11	2.77
	30°N–60°N	—	—	—	6.00	4.23	3.23
	0°N–30°N	—	—	—	3.00	2.07	1.71
Energy and C Fluxes from Fluxnet	NEE	line plot	model vs obs	model vs obs	—	—	—
	Net radiation				—	—	—
	Latent heat				—	—	—
	Sensible heat				—	—	—
Energy and C Fluxes from Ameriflux	NEE	line plot	model vs obs timeseries plot	model vs obs timeseries plot	6.00	2.46	2.13
	Shortwave Incoming				—	—	—
	Latent heat				9.00	6.38	6.39
	Sensible heat				9.00	4.90	4.64
	GPP				6.00	3.39	3.46
	ER				—	—	—
	Aboveground live biomass in South...	obs amazon	model amazon	amazon map	10.00	5.28	4.00

Done

Score Sheet for CLAMP - Mozilla Firefox

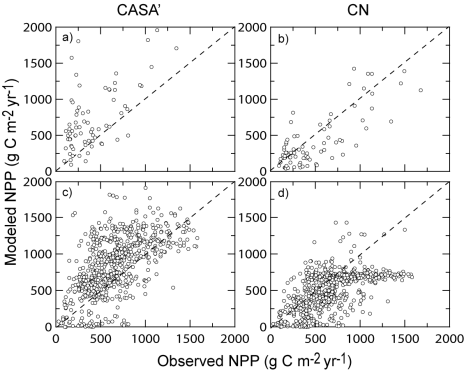
File Edit View History Bookmarks Tools Help

http://www.climatemodeling.org/c-lamp/results/diagnostics/CN_vs_CA

CO_2 Seasonal Cycle — Comparison with Globalview phase and amplitude	60°N–90°N	—	—	—	6.00	4.11	2.77
	30°N–60°N	—	—	—	6.00	4.23	3.23
	0°N–30°N	—	—	—	3.00	2.07	1.71
Energy and C Fluxes from Fluxnet	NEE	line plot	model vs obs	model vs obs	—	—	—
	Net radiation				—	—	—
	Latent heat				—	—	—
	Sensible heat				—	—	—
Energy and C Fluxes from Ameriflux	NEE	line plot	model vs obs timeseries plot	model vs obs timeseries plot	6.00	2.46	2.13
	Shortwave Incoming				—	—	—
	Latent heat				9.00	6.38	6.39
	Sensible heat				9.00	4.90	4.64
	GPP				6.00	3.39	3.46
	ER				—	—	—
Carbon Stocks and Transient Dynamics	Aboveground live biomass in South America	obs amazon	model amazon model vs obs	amazon map model vs obs	10.00	5.28	4.99
	Aboveground live biomass within Amazon Basin (sum within Legal Amazon)	mask obs masked 68.90 (Pg C)	model masked model vs obs 198.87 (Pg C)	model masked model vs obs 160.61 (Pg C)	—	—	—
	NPP Stimulation from elevated CO_2	—	FACE Site table biome table	FACE Site table biome table	10.00	7.87	4.11
	Interannual variability of global carbon fluxes - comparison with TRANSCOM	—	—	—	5.00	3.55	3.00
	Turnover times and pool sizes	—	Leaf Wood Fine Root Litter Coarse Woody Debris Soil	Leaf Wood Fine Root Litter Coarse Woody Debris Soil	—	—	—
	Carbon Sinks (1990–2004)	—	biome mean biome total	biome mean biome total	—	—	—
	Fire Variability (1997–2004)	—	—	global spatial comparison temporal dynamics	5.00	—	1.70
				Total Score	**100.00**	**65.74**	**58.38**

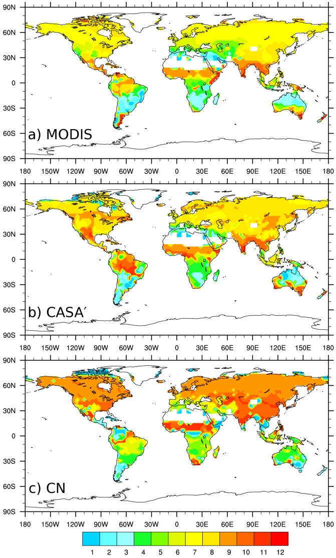
Done

- 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).

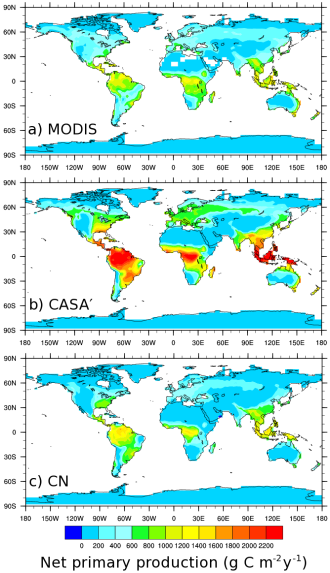


Data provided by NASA Distributed Active Archive Center (DAAC) at ORNL

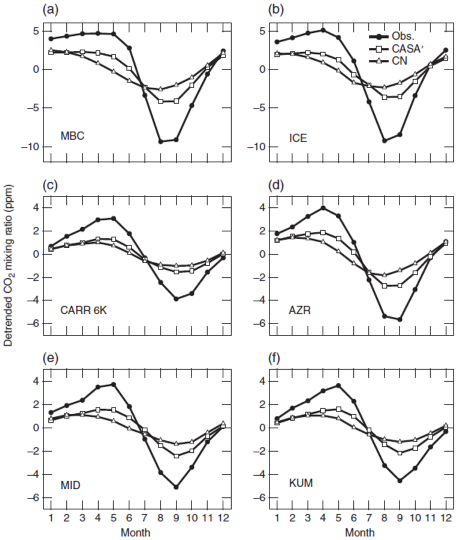
- Comparisons with satellite "modeled observations" must be made carefully because of high uncertainty.
- This comparison with MODIS leaf area index (LAI) focuses on the month of maximum LAI (phase), a measurement with less uncertainty than the "observed" LAI values.
- C-LAMP accounts for this uncertainty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



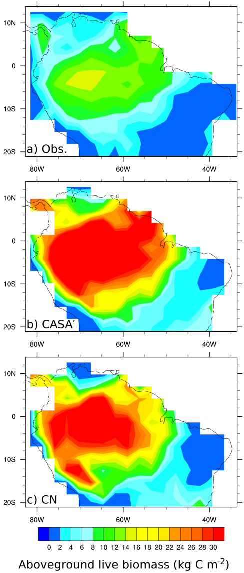
- MODIS net primary production (NPP) "observations" have higher uncertainty.
- Comparison with MODIS NPP focuses on correlation of spatial patterns.
- CLM-CASA′ scored 1.6/2.0 while CLM-CN scored 1.4/2.0.



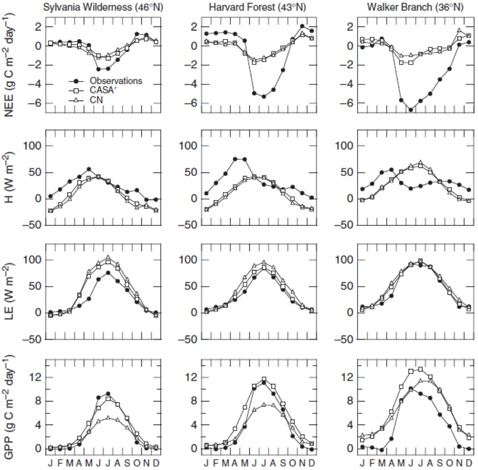
- Comparisons with Globalview flask sites are made by combining model fluxes with impulse response functions from TRANSCOM.
- Shown are the annual cycles of atmospheric CO_2 at (a) Mould Bay, Canada (76°N), (b) Storhofdi, Iceland (63°N), (c) Carr, Colorado (41°N), (d) Azores Islands (39°N), (e) Sand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



- 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.

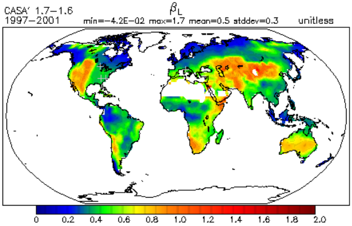


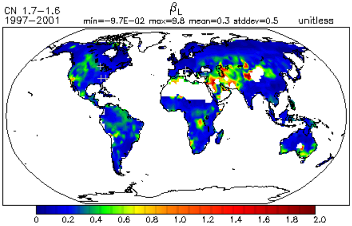
- Comparisons with AmeriFlux eddy correlation CO_2 flux tower sites include net ecosystem exchange (NEE), gross primary production (GPP), respiration, shortwave incoming radiation, and latent and sensible heat.
- Shown here is a comparison of model estimates with eddy covariance measurements from Sylvania Wilderness, Harvard Forest, and Walker Branch.
- Used are the consistent Level 4 data produced by Dario P. and Markus R.

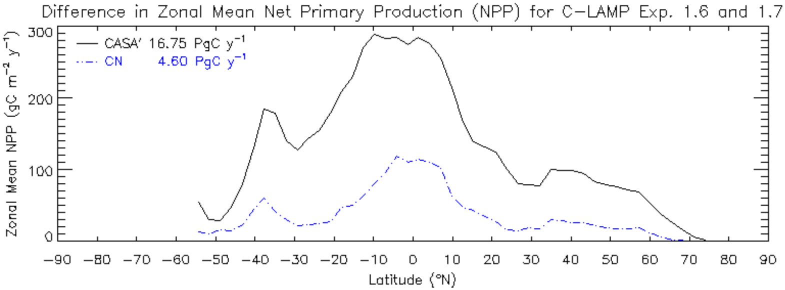


Data provided by ORNL Carbon Dioxide Information Analysis Center (CDIAC).

- 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 $23 \pm 2\%$."
- A C-LAMP experiment was added to test this result by increasing [CO_2] to 550 ppmv in 1997.







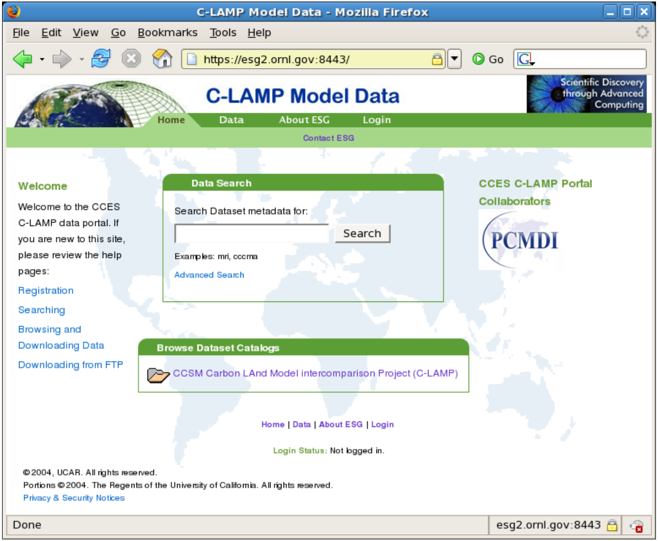
Site Name	Lon (°E)	Lat (°N)	Observations NPP↑	Observations β_L	CASA′ NPP↑	CASA′ β_L	CASA′ Score	CN NPP↑	CN β_L	CN Score
Duke	-79.08	35.97	28.0%	0.69	16.4%	0.41	0.26	6.2%	0.15	0.65
Aspen	-89.62	45.67	35.2%	0.87	15.6%	0.39	0.39	12.4%	0.31	0.48
ORNL	-84.33	35.90	23.9%	0.59	17.3%	0.43	0.16	5.2%	0.13	0.64
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 flash 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 & 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



Biases and Weaknesses Exposed by the C-LAMP Analysis

- Both models had a low LAI bias in boreal and arctic regions. This bias was partially eliminated by a new hydrology model capturing freeze-thaw dynamics.
- Both models had a 1–3 month delay in the timing of maximum LAI. This bias was reduced in CLM3-CN where it was most significant.
- Both models overestimate woody biomass in the Amazon Basin. Carbon comparisons with Malhi *et al.* (in press) suggest too much allocation to wood. Allocation in CLM3-CN was adjusted to reduce this bias.
- The models differed by a factor of two in annual carbon sinks. Both results are compatible with atmospheric budgets given other uncertainties.

Biases and Weaknesses Exposed by the C-LAMP Analysis

- Both models underestimated the amplitude of the seasonal cycle of CO_2 in the northern hemisphere. Adjustment of the Q_{10} for heterotrophic respiration from 2.0 to 1.5 in CLM3-CASA′ reduces this bias. Adoption of the same Q_{10} formulation, in place of Lloyd & Taylor, reduces this bias in CLM3-CN. The Q_{10} for maintenance respiration in CLM3-CN was also reduced from 2.0 to 1.5.
- CLM3-CN seasonal cycle was out of phase with observations. A new day-length control on photosynthesis mechanism mitigates this bias in CLM3-CN.

Global Change Biology

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Systematic assessment of terrestrial biogeochemistry in coupled climate–carbon models

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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

Recent Progress

- 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.
- While our recent proposal to deploy C-LAMP as a web service was not funded, we are sharing the data and diagnostics package for others to use (*e.g.*, Jena's JEDI model) and hoping to incorporate additional metrics over time.
- Next: N-LAMP — develop a strategy for benchmarking the nitrogen cycle in land surface models.

C-LAMP, C^4MIP, and iLEAPS

- C-LAMP Experiment 2 is patterned after C^4MIP (Coupled Climate-Carbon Cycle Model Intercomparison Project, http://www.c4mip.cnrs-gif.fr/) Phase 1.
- At the October 2006 C^4MIP Workshop at the UK Met Office in Exeter, there was strong interest in Experiment 1 and validation experiments using Fluxnet observations.
- At the Marie Curie/iLEAPS Workshop in Hyères in November 2008, a number of modeling groups expressed interest in consistent model validation and model-data comparisons for their coupled biosphere models. See write up in iLEAPS Newsletter number 7.
- A QUEST/GLASS model benchmarking workshop was held in June 2009 at the University of Exeter where a strategy was discussed for combining Australian, European, and U.S. efforts toward a truly international benchmarking system.

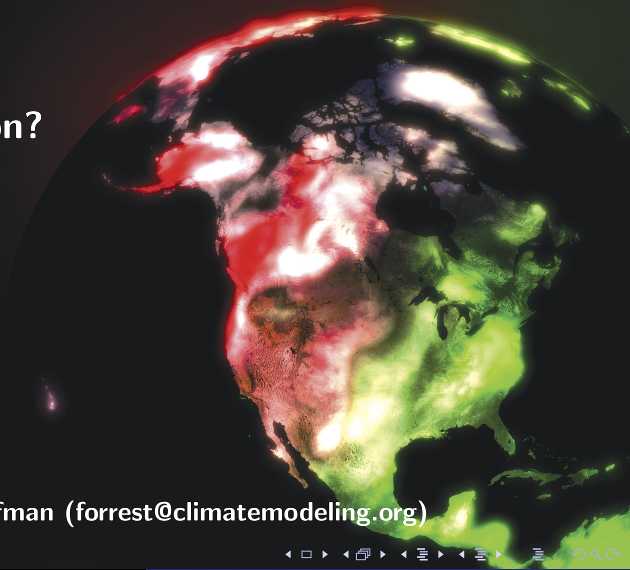
C-LAMP + ILAMB + · · ·

- We believe that C-LAMP and ILAMB should serve as a prototype for a wider international benchmarking activity, the results of which could contribute to AR5.
- Needed are
  1. a well-crafted protocol that exercises model capabilities for simulating energy, water, and biogeochemical cycles;
  2. model output data and metadata standards to simplify subsequent analyses;
  3. best-available forcing data sets; and
  4. best-available observational data sets and diagnostics.
- Follow-on discussions were held by carbon cycle researchers at ICDC8 in Jena in September.
- We plan to finalize the protocol, output standards, metrics and diagnostics, and relationship to AR5 simulations at a meeting in Summer 2010 in the U.S.

Thank you!

Questions?

More Discussion?



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