Quantifying and Reducing Uncertainties Associated with Biogeochemical Feedbacks in Earth System Models

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Biogeochemistry–Climate Feedbacks Research

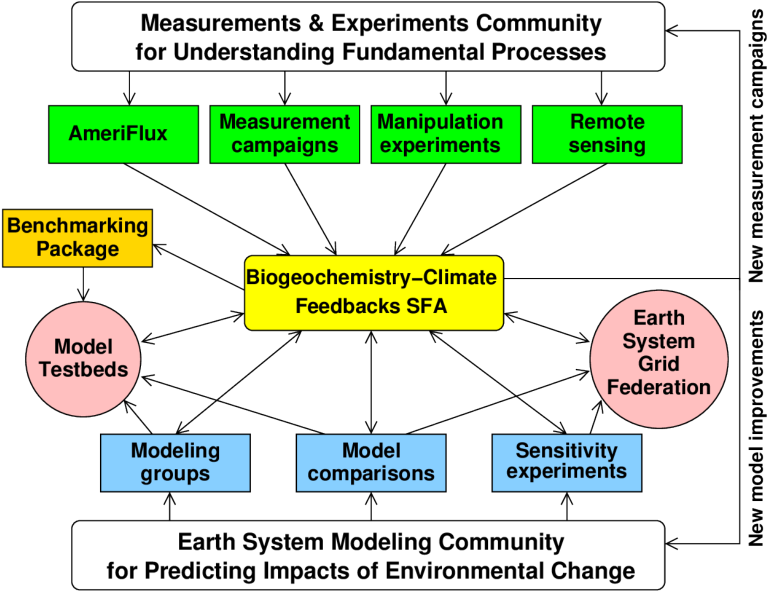
Biogeochemistry Feedbacks Goals

The overarching goals of our biogeochemistry feedbacks research are to identify and quantify the feedbacks between biogeochemical cycles and the climate system, and to quantify and reduce uncertainties in Earth system models (ESMs) associated with those feedbacks.

Our multi-institutional team is

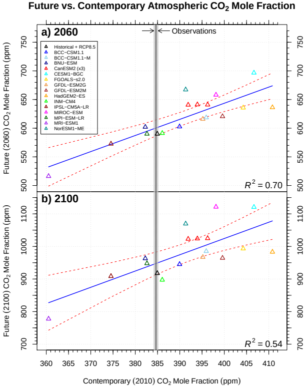
- developing new hypothesis-driven approaches for evaluating ESM process representations at site, regional and global scales;
- investigating the degree to which contemporary observations can be used to reduce uncertainties in future scenarios (e.g., emergent constraints);
- developing open source benchmarking software tools that leverage laboratory, field, and remote sensing data sets for systematic evaluation of ESM biogeochemical processes; and
- evaluating the performance of biogeochemical processes and feedbacks in multiple ESMs using benchmarking tools.

Biogeochemistry–Climate Feedbacks SFA Diagram

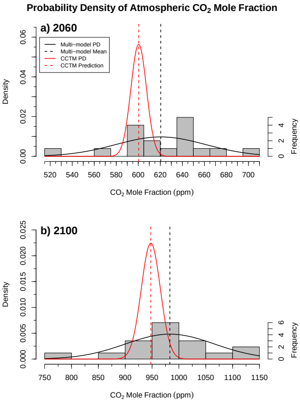


Emergent Constraint Developed from CMIP5 ESMs

An emergent constraint based on carbon inventories was applied to constrain future atmospheric CO_2 projections from CMIP5 ESMs.



- Much of the model-to-model variation in projected CO_2 during the 21st century is tied to biases that existed during observational era.
- Model differences in the representation of concetration–carbon feedbacks and other slowly changing carbon cycle processes appear to be the primary driver of this variability.
- Range of temperature increases at 2100 slightly reduced, from $5.1 \pm 2.2^\circ$C for the full ensemble, to $5.0 \pm 1.9^\circ$C after applying the emergent constraint.



Best estimate using Mauna Loa CO_2

At 2060: 600 ± 14 ppm, 21 ppm below the multi-model mean

At 2100: 947 ± 35 ppm, 32 ppm below the multi-model mean

Hoffman, Forrest M., James T. Randerson, Vivek K. Arora, Qing Bao, Patricia Cadule, Duoying Ji, Chris D. Jones, Michio Kawamiya, Samar Khatiwala, Keith Lindsay, Atsushi Obata, Elena Shevliakova, Katharina D. Six, Jerry F. Tjiputra, Evgeny M. Volodin, and Tongwen Wu (2014), Causes and implications of persistent atmospheric carbon dioxide biases in Earth system models, *J. Geophys. Res. Biogeosci.*, 119(2):141–162, doi:10.1002/2013JG002381. *Most downloaded JGR-B paper Feb. 2014!*

Drought severity mediated by plant responses to rising CO_2

Objective

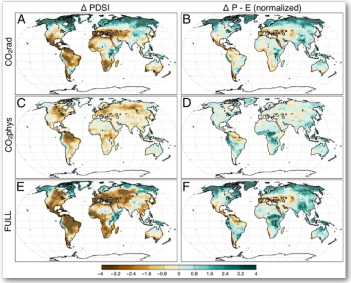
Understand how plant responses to increasing CO_2 affect predictions of future drought stress.

Approach

- Used seven CMIP5 Earth system models (ESMs) to quantify the effect of increasing atmospheric CO_2 on changes in PDSI and P–E drought metrics.
- Three idealized simulations with different CO_2 couplings were used to distinguish climate effects from vegetation effects.

Results/Impacts

- We found that plant physiological responses to CO_2 reduced predictions of future drought stress.
- This reduction was captured by plant-centric rather than atmospheric-centric metrics from ESMs.
- Drought metrics that account for plant transpiration responses to changing CO_2 are needed to reduce uncertainties in future assessments.



Maps of the multimodel mean difference for a quadrupling of CO_2 for (A, C, and E) Palmer Drought Severity Index (PDSI) and (B, D, and F) precipitation minus evapotranspiration (P–E) normalized by the standard deviation of the multimodel mean at each point. Green colors indicate more water on land; brown colors indicate less water on land. A and B represent CO_2 radiative coupling, C and D CO_2 physiological coupling, and E and F full CO_2 coupling.

Swann, A. L. S., F. M. Hoffman, C. D. Koven, and J. T. Randerson (2016), Plant responses to increasing CO_2 reduce estimates of climate impacts on drought severity, *Proc. Nat. Acad. Sci.*, 113(36):10019–10024, doi:10.1073/pnas.1604581113.

Do Climate–Carbon Feedbacks Intensify Over Time?

Objective

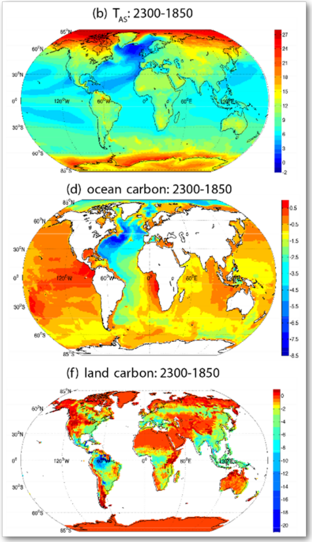
Understand how land and ocean contributions to climate–carbon feedbacks evolve over time from 1850 to 2300.

Approach

- Use CESM1(BGC) to assess carbon cycle dynamics for the Representative Concentration Pathway 8.5 and its extension.
- Three simulations with different levels of radiative coupling allowed us to diagnose parameters describing the gain of the climate–carbon feedback.

Results/Impacts

- We found that the gain of the climate–carbon feedback increased almost three-fold from 2100 to 2300.
- Ocean carbon sensitivity to climate change was proportional to increases in heat content.
- Climate influence on carbon was largest in the Atlantic Ocean and in Central and South American forests.



Randerson, J. T., K. Lindsay, E. Muñoz, W. Fu, J. K. Moore, F. M. Hoffman, N. M. Mahowald, and S. C. Doney (2015), Multicentury Changes in Ocean and Land Contributions to Climate–Carbon Feedbacks, *Global Biogeochem. Cycles*, 29(6):744–759, doi:10.1002/2014GB005079.

Land use change & carbon cycle feedback interactions

Objective

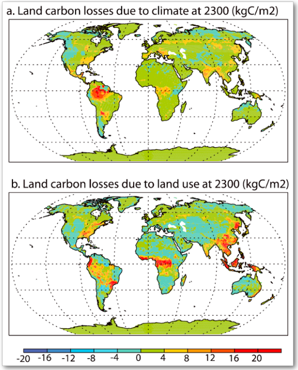
Quantify the impact of human land use and land cover change (LULCC) on the terrestrial carbon budget to year 2300.

Approach

- Used an Earth system model (ESM) forced with Representative Concentration Pathway 8.5 (RCP8.5).
- Accounted for direct and quasi-direct LULCC CO_2 emissions as well as the influence of LULCC on reducing natural carbon sinks in the future.

Results/Impacts

- Conversion of land (e.g., from forest to croplands via deforestation) resulted in a model-estimated, cumulative carbon loss of 490 Pg C between 1850 and 2300.
- About 40% of carbon loss associated with LULCC arose from direct human modification of land surface; remaining 60% was indirect consequence of loss of potential natural carbon sinks.
- Most anthropogenic carbon uptake resulted from effect of rising atmospheric CO_2 on photosynthesis in trees, indicating model-projected carbon feedbacks were sensitive to deforestation.



Change in land carbon at year 2300 caused by (a) climate change from CO_2 and other forcing agents, and (b) human land use and land cover change.

Mahowald, Natalie M., James T. Randerson, Keith Lindsay, Ernesto Muñoz, Scott C. Doney, Peter Lawrence, Sarah Schlunegger, Daniel S. Ward, David M. Lawrence, and Forrest M. Hoffman (2017), Interactions between land use change and carbon cycle feedbacks, *Global Biogeochem. Cycles*, 31(1):96–113, doi:10.1002/2016GB005374.

ESMs overestimate wood C allocation & total biomass

Objective

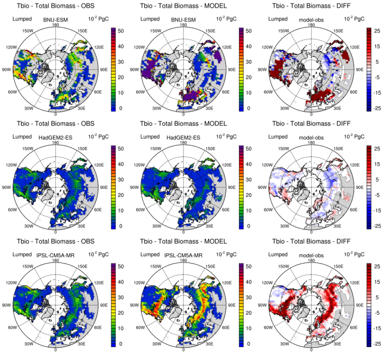
Evaluate predicted vegetation biomass and allocation for Northern Hemisphere extratropics in CMIP5 Earth system models (ESMs).

Approach

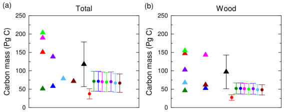
- We used forest biomass data synthesized from radar remote sensing and ground-based measurements across northern extratropics.
- We evaluated leaf, wood, and root carbon density and total carbon biomass for CMIP5 ESMs.

Results/Impacts

- We found that most ESMs overestimated wood carbon stocks and total biomass, likely a result of excessive carbon allocation to wood.
- Total forest biomass was primarily positively correlated with precipitation variations, with temperature becoming equally important at higher latitudes, in models and observations.
- Results suggest parametric or structural model differences are a larger source of uncertainty than differences in transient responses.



Comparison of projected total biomass from three models (middle column) compared to observational estimates remapped to the model grids (left column) and resulting bias maps (right column).



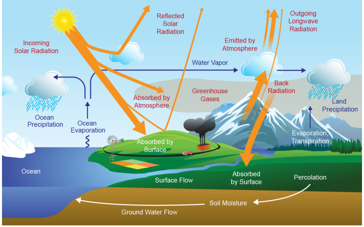
Global (a) total and (b) wood carbon mass from models (triangles) and observations (circles).

Yang, C.-E., J. Mao, F. M. Hoffman, D. M. Ricciuto, J. S. Fu, C. D. Jones, and M. Thurner (2017), Uncertainty quantification of extratropical forest biomass in CMIP5 models over the Northern Hemisphere, *Scientific Reports*, submitted.

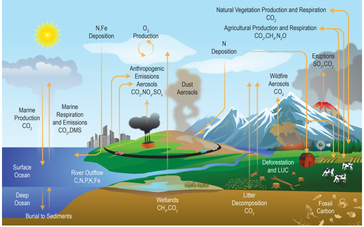
What is ILAMB?

A community coordination activity created to:

- **Develop internationally accepted benchmarks** for land model performance by drawing upon collaborative expertise
- **Promote the use of these benchmarks** for model intercomparison
- **Strengthen linkages between experimental, remote sensing, and climate modeling communities** in the design of new model tests and new measurement programs
- **Support the design and development of open source benchmarking tools** (Luo et al., 2012)



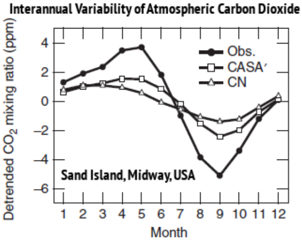
Energy and Water Cycles



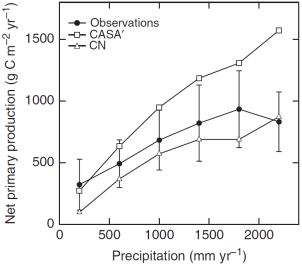
Carbon and Biogeochemical Cycles

What is a Benchmark?

- A **benchmark** is a quantitative test of model function achieved through comparison of model results with observational data.
- Acceptable performance on benchmarks **is a necessary but not sufficient condition** for a fully functioning model.
- **Functional benchmarks** offer tests of model responses to forcings and yield insights into ecosystem processes.
- Effective benchmarks must draw upon a broad set of independent observations to evaluate model performance on **multiple temporal and spatial scales**.



Models often fail to capture the amplitude of the seasonal cycle of atmospheric CO_2.



Models may reproduce correct responses over only a limited range of forcing variables.

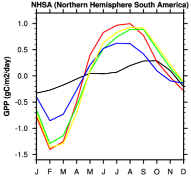
(Randerson et al., 2009)

Why Benchmark?

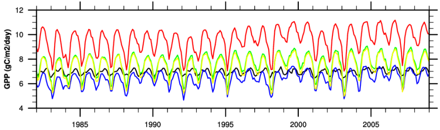
- **to demonstrate model improvements** in representation of coupled climate and biogeochemical cycles
- **to quantitatively diagnose impacts of model development** in related fields on carbon cycle processes
- **to guide synthesis efforts**, such as the Intergovernmental Panel on Climate Change (IPCC), in assessing model fidelity
- **to increase scrutiny of key datasets** used for model evaluation
- **to identify gaps in existing observations** needed for model validation
- **to accelerate incorporation of new measurements** for rapid and widespread use in model assessment
- **to provide a quantitative, application-specific set of minimum criteria** for participation in model intercomparison projects (MIPs).

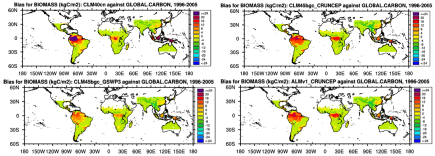
Current Status of the ILAMB Packages

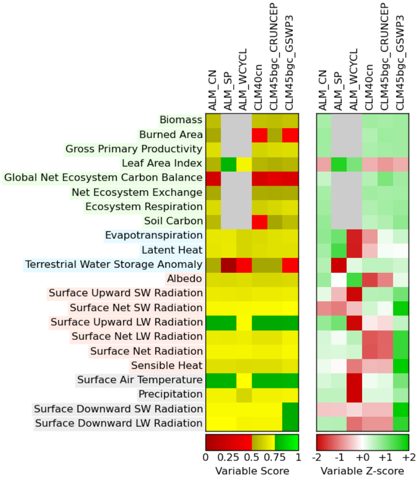
- **ILAMBv1** released at 2015 AGU Town Hall, doi:10.18139/ILAMB.v001.00/1251597
- **ILAMBv2** released at 2016 ILAMB Workshop, doi:10.18139/ILAMB.v002.00/1251621
- Being used for ACME and CESM evaluation



Model	Annual	Bias	RMSE
FLUXNET-MTE	6.95	-999.00	-999.00
CLM40cn	9.55	2.60	2.73
CLM45bgc_CRUNCEP	7.62	0.67	0.96
CLM45bgc_GSWP3	6.42	-0.53	0.71
ALMv1_CRUNCEP	7.43	0.48	0.89







ILAMB Prototype Diagnostics System

- Current variables:
  Aboveground live biomass (Contiguous US, Pan Tropical Forest), Burned area (GFED3), CO_2 (NOAA GMD, Mauna Loa), Gross primary production (Fluxnet, MTE), Leaf area index (AVHRR, MODIS), Global net land flux (GCP, Khatiwala/Hoffman), Net ecosystem exchange (Fluxnet, GBA), Ecosystem Respiration (Fluxnet, GBA), Soil C (HWSD, NCSCDv2), Evapotranspiration (GLEAM, MODIS), Latent heat (Fluxnet, MTE), Soil moisture (ESA), Terrestrial water storage anomaly (GRACE), Albedo (CERES, GEWEX, MODIS), Surface up SW/LW radiation (CERES, GEWEX.SRB, WRMC.BSRN), Sensible heat (Fluxnet, GBA), Surface air temperature (CRU, Fluxnet), Precipitation (Fluxnet, GPCC, GPCP2), Surface down SW/LW radiation (Fluxnet, CERES, GEWEX.SRB, WRMC.BSRN),
- Graphics and scoring systems:
  - Annual mean, Bias, RMSE, seasonal cycle, spatial distribution, interannual coeff. of variation and variability, long-term trend scores
  - Global maps, variable to variable, and time series comparisons
- Software:
  Freely distributed, designed to be user friendly and to enable easy addition of new variables

ILAMBv2 Layout

ILAMB Benchmark F

climate.ornl.gov/~ncf/ILAMB-next/

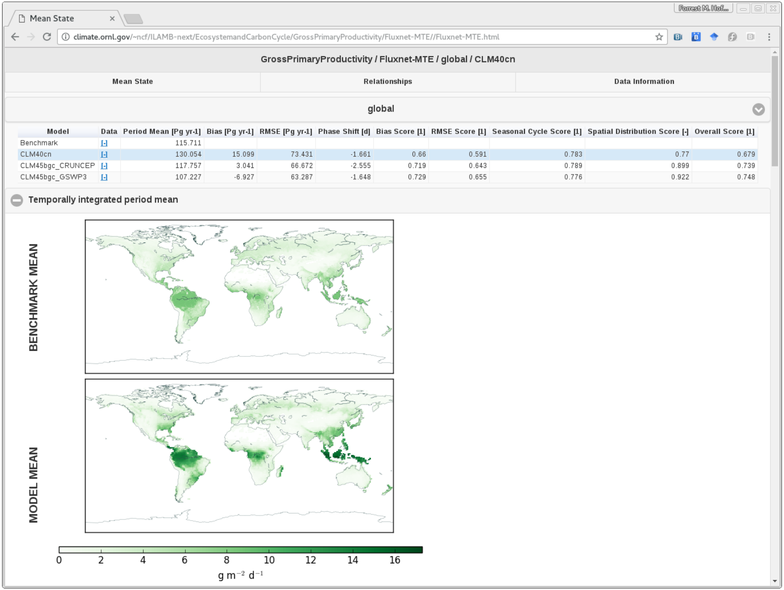
ILAMB Benchmark Results

Overview | Results Table

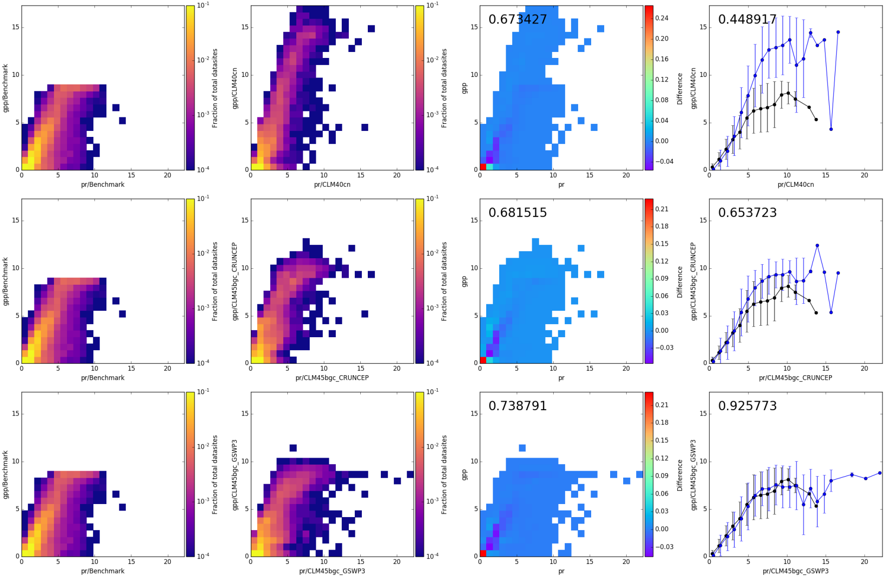
Columns...

	CLM40cn	CLM45bgc_CRUNCEP	CLM45bgc_GSWP3
Biomass	0.63	0.65	0.70
Burned Area	0.35	0.49	0.50
Gross Primary Productivity	0.68	0.72	0.74
Leaf Area Index	0.51	0.50	0.56
Global Net Ecosystem Carbon Balance	0.27	0.34	0.30
GCP (50.0%)	0.36	0.48	0.44
Hoffman (50.0%)	0.18	0.21	0.16
Net Ecosystem Exchange	0.49	0.48	0.49
Ecosystem Respiration	0.63	0.68	0.72
Soil Carbon	0.45	0.51	0.65
Evapotranspiration	0.73	0.76	0.78
Latent Heat	0.78	0.80	0.81
Terrestrial Water Storage Anomaly	0.50	0.50	0.48
Albedo	0.74	0.74	0.75
CERES (33.3%)	0.77	0.77	0.78
GEWEX.SRB (33.3%)	0.69	0.70	0.70
MODIS (33.3%)	0.75	0.75	0.76
Surface Upward SW Radiation	0.79	0.79	0.80
Surface Net SW Radiation	0.87	0.87	0.89
Surface Upward LW Radiation	0.94	0.94	0.95
Surface Net LW Radiation	0.78	0.79	0.84

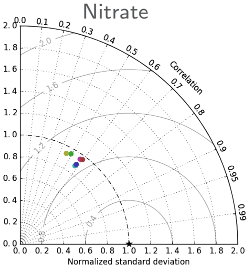
ILAMBv2 Layout

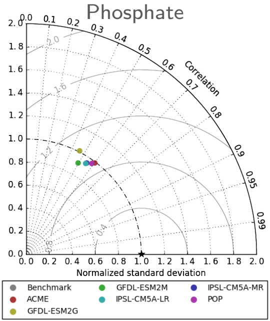


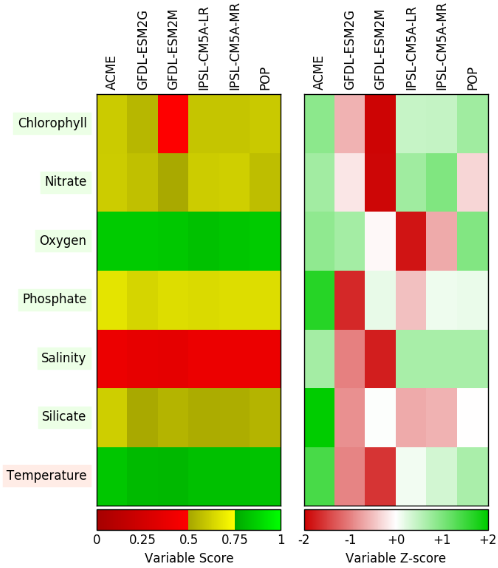
ILAMBv2 Relationships (Under Development)



Extending ILAMB for Ocean Model Evaluation







Second US ILAMB Workshop, May 16–18, 2016

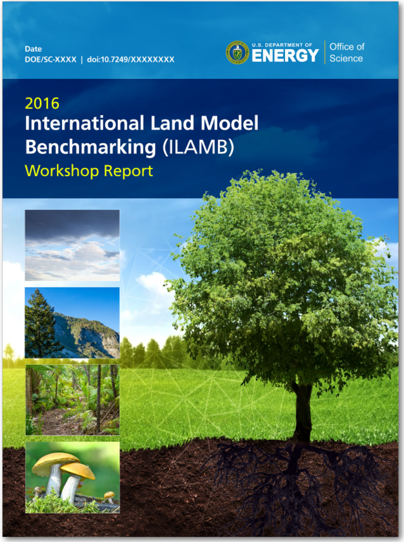
Overarching Workshop Goals

Engage the research community in defining scientific priorities for

- Design of new metrics for model benchmarking
- Model Intercomparison Project (MIP) evaluation needs
- Model development, testbeds, and workflow practices
- Observational data sets and needed measurements

Workshop Attendance

- 60+ participants from Australia, Japan, China, Germany, Sweden, Netherlands, UK, and US
- 10 modeling centers represented
- ∼25 online attendees at any time



doi:10.2172/1330803

2016 ILAMB Workshop Synthesis

Integrating and Cross-cutting Themes
- Process-specific experiments
- Metrics from extreme events
- Design of new perturbation experiments
- High latitude processes
- Tropical processes
- Remote sensing
- Eddy covariance flux networks

Model Intercomparison Projects (MIPs)
- CMIP6 DECK
- Coupled Climate–Carbon Cycle (C4MIP)
- Land Surface, Snow, and Soil Moisture (LS3MIP)
- Multi-scale Synthesis & Terrestrial (MsTMIP)
- Processes Linked to Uncertainties Modeling Ecosystems (PLUME-MIP)

Major Processes
- Ecosystem processes and states
- Hydrology
- Atmospheric CO_2
- Soil carbon and nutrient biogeochemistry
- Surface fluxes
- Vegetation dynamics

Benchmarking Approaches
- Statistical comparisons (bias, RMSE, etc.)
- Functional response or variable-to-variable
- Emergent constraints
- Reduced complexity models & traceability
- Formal uncertainty quantification
- Meta-analyses of perturbation experiments

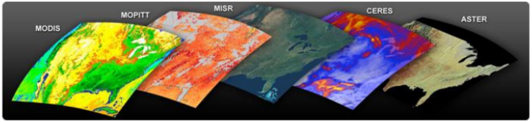
Benchmarking Challenges and Priorities
- Develop super site benchmarks integrated with AmeriFlux and FLUXNET
- Create benchmarks for soil carbon turnover and vertical distribution and transport
- Develop benchmark metrics for extreme event statistics and response of ecosystems
- Synthesize data for vegetation recruitment, growth, mortality, and canopy structure
- Create benchmarks focused on critical high latitude and tropical forest ecosystems
- Leverage observational projects and create a roadmap for remote sensing methods

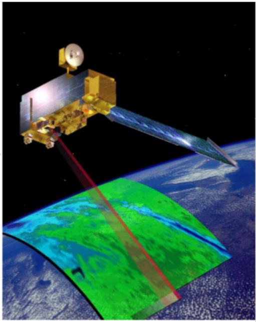
Enabling Capabilities
- Model development and new output variables
- Land model testbeds (LMTs)
- Field measurements and monitoring activities
- Perturbation experiments and lab studies
- Observational data archives and repositories
- Computational resources and infrastructure

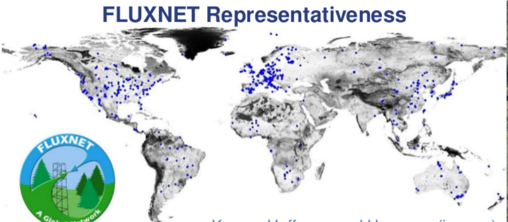
Benchmarking Advances
- Process understanding
- Quantified feedbacks
- Reduced uncertainties
- Improved model projections

Benchmarking Challenges and Priorities

- **Super site benchmarks** for AmeriFlux and FLUXNET
- **Benchmarks for soil carbon** turnover, distribution, transport
- **Metrics for extreme events** & response of ecosystems
- **Data for vegetation** recruitment, growth, mortality, phenology, canopy structure
- Benchmarks for critical **high latitude & tropical ecosystems**
- Leverage **field projects & remote sensing methods**







Kumar, Hoffman, and Hargrove (in prep)

Future ILAMB Developent and Application

- ILAMBv1 and ILAMBv2 were applied to:
  - CMIP5 Historical and esmHistorical simulations
  - ACME (now called E3SM) Land Model evaluation
  - Model development of the Community Land Model (CLM5)
- ILAMBv2 use in U.S. Department of Energy projects:
  - NGEE Arctic, NGEE Tropics, and SPRUCE are adopting the framework for evaluating process parameterizations & integrating field observations
  - ACME is developing metrics for evaluation of new land model features
  - BGC Feedbacks is developing the framework and benchmarking MIPs
- Future projects where we hope to apply ILAMB:
  - CMIP6, including C^4MIP, LS3MIP, and LUMIP
  - TRENDY
  - PLUME-MIP
- Others are using and contributing to ILAMB:
  - a NASA-funded Permafrost Benchmarking System
  - in-house model evaluation at Hadley Center, U. Tokyo, MPI-Met

Acknowledgments

U.S. DEPARTMENT OF ENERGY

Office of Science

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