Reducing Uncertainty in Biogeochemical Interactions Through Synthesis and Computation

The RUBISCO Scientific Focus Area (SFA)

E3SM Coupled Biogeochemistry Group (CBGC) Webinar

October 29, 2019

U.S. DEPARTMENT OF ENERGY

Office of Science

RUBISCO

US Dept. of Energy's RUBISCO Scientific Focus Area (SFA)

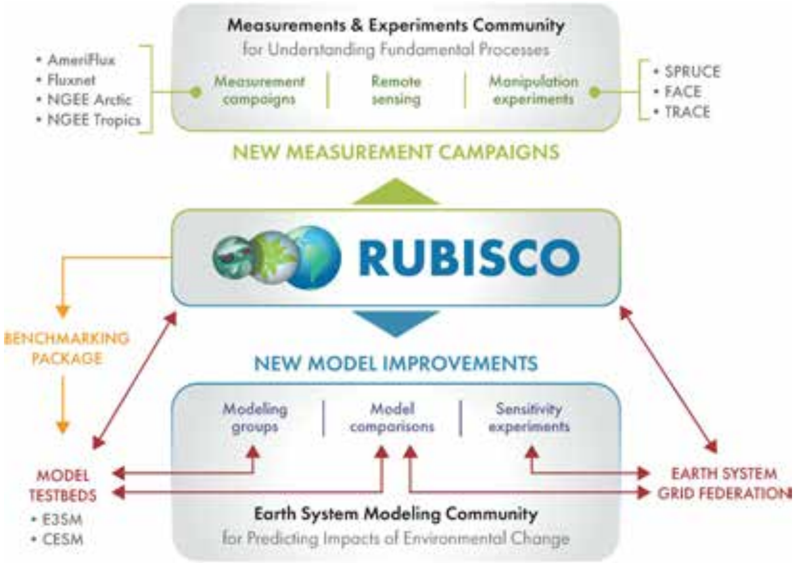
Forrest M. Hoffman (Laboratory Research Manager), William J. Riley (Senior Science Co-Lead), and James T. Randerson (Chief Scientist)

Research Goals

- Identify and quantify interactions between biogeochemical cycles and the Earth system
- Quantify and reduce uncertainties in Earth system models (ESMs) associated with interactions

Research Objectives

- Perform hypothesis-driven analysis of biogeochemical & hydrological processes and feedbacks in ESMs
- Synthesize in situ and remote sensing data and design metrics for assessing ESM performance
- Design, develop, and release the International Land Model Benchmarking (ILAMB) and International Ocean Model Benchmarking (IOMB) tools for systematic evaluation of model fidelity
- Conduct and evaluate CMIP6 experiments with ESMs



The RUBISCO SFA works with the measurements and the modeling communities to use best-available data to evaluate the fidelity of ESMs. RUBISCO identifies model gaps and weaknesses, informs new model development efforts, and suggests new measurements and field campaigns.

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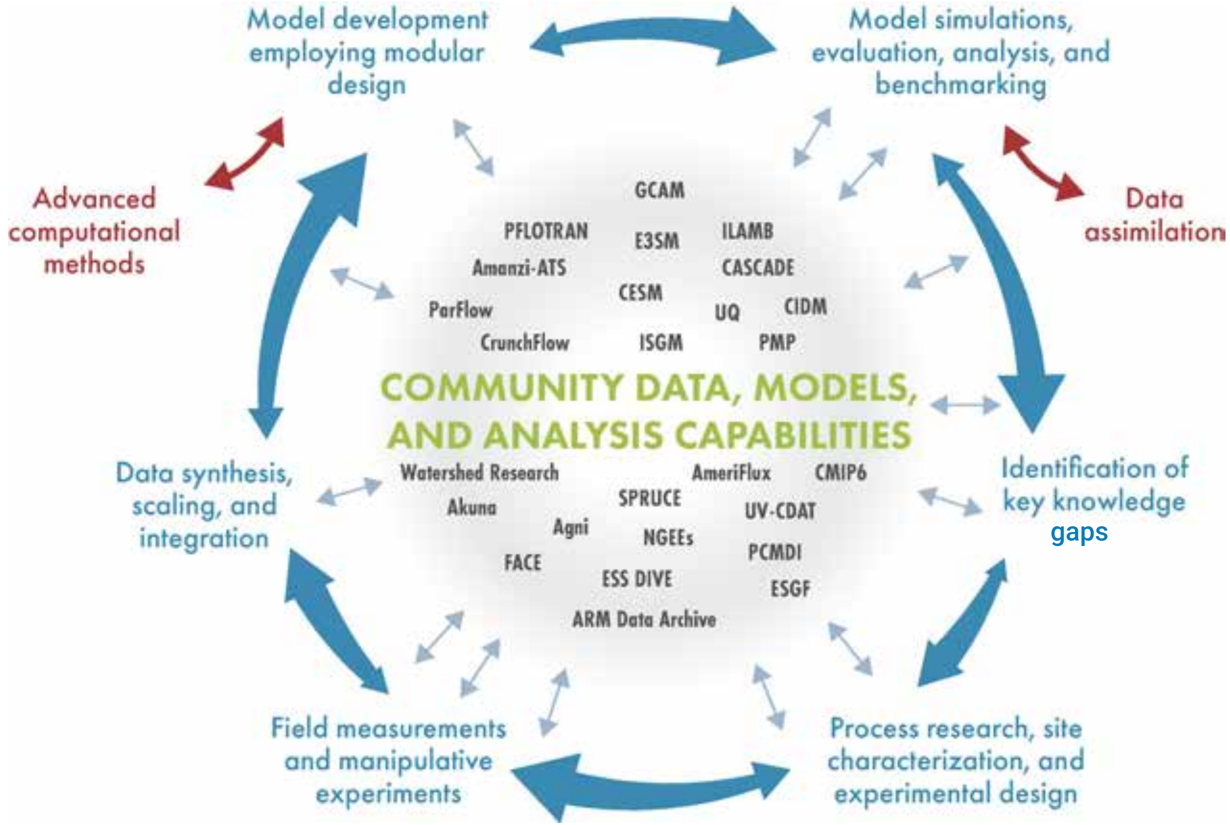
DOE's Model-Data-Experiment Enterprise

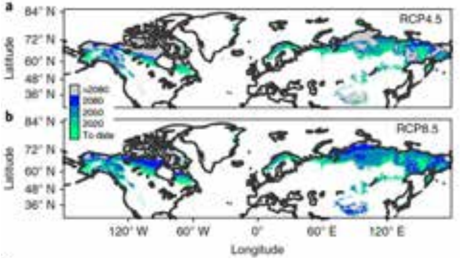


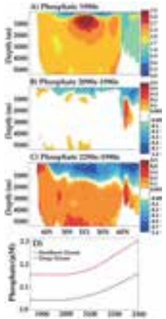
RUBISCO SFA Nine Partner Institutions

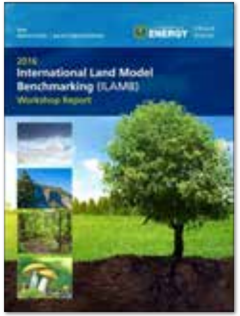
- **5 National Labs**
  - Argonne
  - Brookhaven
  - Los Alamos
  - Lawrence Berkeley
  - Oak Ridge
- **National Center for Atmospheric Research (NCAR)**
- **3 Universities**
  - UC Irvine
  - U. Michigan
  - N. Arizona U.

RUBISCO SFA Research and Development Activities

- Major contributions to organizing sessions and presenting science at the AGU Fall Meeting, AGU Chapman Conference, and ESA Annual Meeting
- Strong interactions between **RUBISCO**, **E3SM**, and **CESM** for land and ocean biogeochemistry simulations and evaluation in **ILAMB** and **IOMB**
- F. Hoffman, C. Koven, and J. Randerson participate on **C4MIP** SSC; D. Lawrence leads **LUMIP** SSC; J. Mao participates on **LS3MIP** SSC for **CMIP6**
- W. Riley (former co-chair), D. Lawrence (co-chair), C. Koven (co-chair), and J. Tang participate in **CESM Land Model Working Group**
- J. Randerson (former co-chair), G. Keppel-Aleks (co-chair), and F. Hoffman participate in **CESM Biogeochemistry Working Group**
- J. Randerson, W. Riley, P. Levine, and Q. Zhu participate in **International Soil Radiocarbon Database (ISRaD)** project
- Leading **Soil Carbon Dynamics Working Group** and **RUBISCO-AmeriFlux Working Group** aimed at improving datasets and evaluation metrics
- Participating with NCAR, GFDL, PNNL, ORNL & universities on two new NOAA/DOE co-funded **NOAA Climate Process Team (CPT) projects**







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RUBISCO SFA Research Productivity and Impact

- **Our multi-institutional SFA is unique in:**
  - Focusing on biogeochemical feedbacks in the Earth system (requires multidisciplinary expertise, access to high performance computing, and use of fully coupled ESMs)
  - Exploring coupling across different reservoirs and long-range ecological teleconnections
  - Delivery of unique tools to community for BGC model evaluation (ILAMB, IOMB)
  - Being a focal point for community engagement (Biogeochemistry Science Friday, Topical Working Groups, ILAMB Tutorials, CMIP6 Hackathon)
- **Major accomplishments from Phase 2 of the SFA include:**
  - ILAMB development and application in international activities
  - New high impact science on global biogeochemical cycles
  - Community engagement activities

RUBISCO SFA Accomplishments

- Publication of ILAMBv2 design paper in *JAMES* (Collier et al., 2018)
- Systematic use of ILAMBv2 to develop and validate:
  - ELMv1 (Zhu et al., 2019; Burrows et al., in review)
  - CLM5 (Bonan et al., 2019; Lawrence et al., in press)
- Use of ILAMBv2 by the Global Carbon Project to evaluate TRENDY models (Le Quéré et al., 2018)
- ILAMBv2 is widely used by the international modeling community (MPI, Hadley Centre, Canadian Climate Centre, U. Tokyo, ...)
- An ILAMBv2 evaluation figure is included in the Chapter 5 draft of IPCC AR6
- **We published 37 papers in FY2018** and **43 papers in FY2019 (so far)**
  - 2 *Science* series and 15 *Nature* series
  - 5.3 papers/person time (FY2018) – **high productivity!**
  - >10,000 cumulative citations (superlinear increase); 2,431 citations/yr (CY2018) – **high impact!**

RUBISCO SFA Recent Science (1/2)

- First application of Detection & Attribution (D&A) methodology to terrestrial biogeochemistry and hydrology (Mao et al., 2016; Forbes et al., 2019a, 2019b)
- Novel information transfer methods to infer coupling between land, atmosphere, and ocean (Liu et al., 2019)
- First mechanistic explanation of fire effects on high-latitude vegetation and C cycling (Mekonnen et al., 2019)
- Discovery of a new ecological teleconnection by which loss of Antarctic sea ice triggers massive loss of global marine productivity and fisheries (Moore et al., 2018) - *Part of a series of long-term ecological response papers (Randerson et al., 2015; Hoffman, 2015; Mahowald et al., 2017; Sharma et al., in prep)*

RUBISCO SFA Recent Science (2/2)

- First estimate of temperature limitations on C cycling at high latitude from observations and comparison with CMIP models (Keenan & Riley, 2019)
- First mechanistic explanation of precipitation and soil moisture changes in the Amazon Basin in response to rising atmospheric CO_2 (Langenbrunner et al., 2019; Kooperman et al., 2018a, 2018b)
- First estimation of climate–carbon cycle feedbacks from economic damages (Woodard et al., 2019)
- New constraints on ocean nutrient distributions (Wang et al., 2019; Martiny et al., 2019)
- New understanding of the impact of land–atmosphere coupling on temperature and the carbon during the evolution of El Niño using E3SM (Levine et al., 2019)

Science Highlights

Biogeochemical Detection & Attribution (D&A)

Contribution of environmental forcings to US runoff changes for the period 1950–2010

Objective: Long-term gridded WaterWatch runoff observations and factorial ensemble simulations from the Multi-scale Synthesis and Terrestrial Model Intercomparison Project (MsTMIP) were used to quantify the natural and anthropogenic controls on US runoff changes for the period 1950–2010.

New Science:

- Annual runoff observations had heterogeneous patterns of change regionally in the US. The eastern two-thirds of the US has seen significant and insignificant increases in annual runoff while the western one-third had a greater significant decrease.
- Autumn runoff significantly increased for the northern and southern regions and the US as a whole. Northern and southern runoff also significantly increased for the winter season. For the west, there was a significant decrease in summer runoff.
- Changes in observational runoff were detected in climate change only simulation for all of the seasons and regions studied (A). While the changes in observational runoff could be detected in and attributed to CO_2 concentration (B), nitrogen deposition (C), and land use and land cover change (D) for certain cases, results were not consistent enough regionally and seasonally to draw any major conclusions.

Significance:

- We detected the changing trends and clarified the environmental driving mechanisms for the US runoff during the 1950–2010 period.
- We succeeded in applying single-factor land surface model simulations to conduct detailed detection and attribution (D&A) analysis in order to address the causality of changes in US runoff.

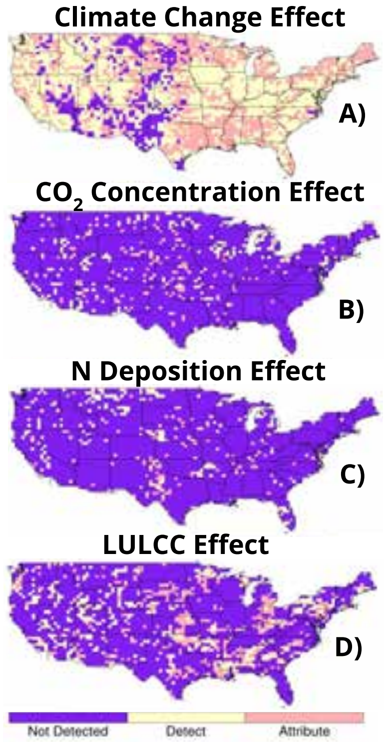

Figure: Spatial patterns of D&A scaling factors. Not detected (purple) denotes a scaling factor whose corresponding 95% confidence interval was less than zero or included zero. If the 95% confidence interval was greater than zero but did not include one, the forcing was detected (yellow). A positive confidence interval was labeled as attributed (pink) if it included one.

Forbes, Whitney L., **Jiafu Mao**, M. Jin, S.-C. Kao, W. Fu, **Xiaoying Shi**, D. M. Ricciuto, P. E. Thornton, A. Ribes, Y. Wang, S. Piao, T. Zhao, C. R. Schwalm, **Forrest M. Hoffman**, J. B. Fisher, A. Ito, B. Poulter, Y. Fang, H. Tian, A. K. Jain, and D. J. Hayes (2018), Contribution of environmental forcings to US runoff changes for the period 1950–2010, *Environ. Res. Lett.*, 13(5), 054023, doi:10.1088/1748-9326/aabb41.

Developing New Model Evaluation Methods

Using Information Theory to Evaluate Directional Precipitation Interactions Over The West Sahel Region In Observations and Models

Objective: To study West Sahel precipitation variation in models and observations with information theory.

Approach: Use "directional information transfer" to assess model fidelity at the process level.

Results/Impacts: We used directional information transfer to gauge West Sahel precipitation variation and found that CMIP5 ESMs represented either the unidirectional control of SST on precipitation or the bidirectional interaction between vegetation and precipitation, but no ESM represented both controls. The GFDL and IPSL-CM5A-LR models successfully reproduced observed patterns over ~50% of the West Sahel, but were not accurate in reproducing observed regional trends or interannual variation of precipitation.

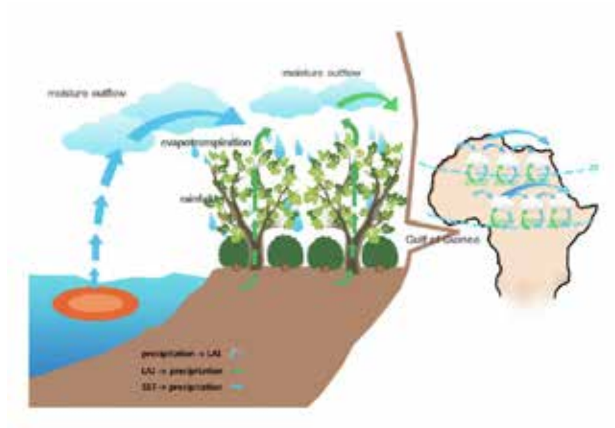

Figure: (a) Emergent benchmarks for West Sahel precipitation from observations and CMIP5 ESMs. (b) Percentage of model grid cells exhibiting interactions consistent with the observed mechanistic benchmark for West Sahel precipitation. SST, LAI, and P are sea surface temperature, leaf area index, and precipitation, respectively.

Liu, B. Y., **Qing Zhu**, **William J. Riley**, L. Zhao, H. Ma, M. Van Gordon, and L. Larsen (2019), Using information theory to evaluate directional precipitation interactions over the West Sahel region in observations and models, *J. Geophys. Res. Atmos.*, 124(3):1463–1473, doi:10.1029/2018JD029160.

Using Information Theory to Evaluate Directional Precipitation Interactions Over The West Sahel Region In Observations and Models

Objective: To study West Sahel precipitation variation in models and observations with information theory.

Approach: Use “directional information transfer” to assess model fidelity at the process level.

Results/Impacts:

- We used observations to infer relationships between SST, vegetation, and West Sahel precipitation (P)
- CMIP5 ESMs represented either SST controls on P or bidirectional interactions between vegetation and P
- Two models reproduced observed patterns over ~50% of the West Sahel, but not regional trends or P IAV
- Benchmark for ILAMB

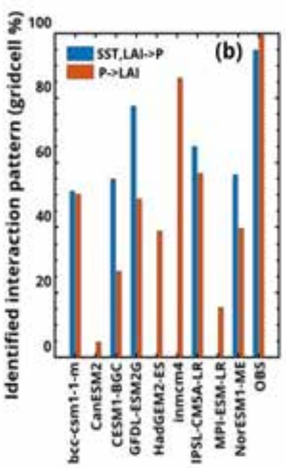

Figure: Percentage of model grid cells exhibiting interactions consistent with the observed mechanistic benchmark for West Sahel precipitation.

Liu, B. Y., **Qing Zhu**, **William J. Riley**, L. Zhao, H. Ma, M. Van Gordon, and L. Larsen (2019), Using information theory to evaluate directional precipitation interactions over the West Sahel region in observations and models, *J. Geophys. Res. Atmos.*, 124(3):1463–1473, doi:10.1029/2018JD029160.

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Ocean Teleconnection on Biogeochemistry

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Sustained Warming Drives Declining Marine Biological Productivity

Objective: To study climate change impacts on marine biogeochemistry and productivity over multi-century timescales.

Approach: Analyze Community Earth System Model (CESMv1.0) simulation to year 2300 with RCP8.5/ECP8.5 scenario (atmospheric CO_2 exceeds 1960 ppm).

Results/Impacts: Increasing biological production and export around Antarctica "traps" nutrients. This drives a net transfer of nutrients to the deep ocean, reducing net primary production (NPP) globally. Declining productivity reduces potential global fishery catch by 20%, with declines of nearly 60% in the North Atlantic.

Moore, J. K., **W. Fu**, F. Primeau, G. L. Britten, K. Lindsay, M. Long, S. C. Doney, N. Mahowald, **F. M. Hoffman**, **J. T. Randerson** (2018), Sustained climate warming drives declining marine biological productivity, *Science*, 359(6380): 1139–1143, doi:10.1126/science.aao6379.

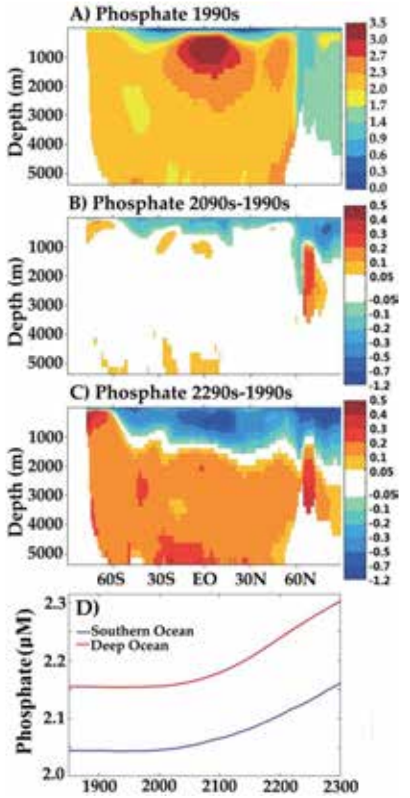

Figure: Antarctic trapping increases nutrient transfer to the deep ocean.

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Plant Physiological Responses to Warming

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Greening of the land surface in the world's cold regions consistent with recent warming

Objective: To infer the response of ecosystems to past and future temperature change

Approach: Combine satellite observations from 1982–2010, CMIP5 ESM projections, and functional responses to analyze vegetation cover changes in the world's cold regions

Results/Impacts:

- Observations indicate a greening of high-latitude ecosystems over the past 3–4 decades, which is related to recent warming and likely to continue
- Observations used to create ESM benchmark
- CMIP5 ESMs exhibit large biases in vegetation cover in high latitude ecosystems

Keenan, T. F., and **W. J. Riley** (2018), Greening of the land surface in the world's cold regions consistent with recent warming, *Nature Clim. Change*, 8(9):825–828, doi:10.1038/s41558-018-0258-y.

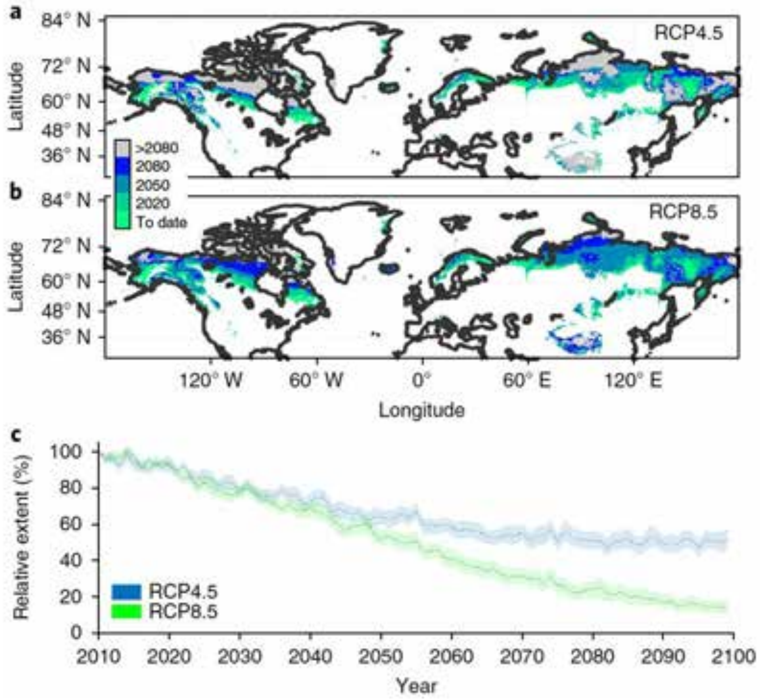

Figure: Observed (GIMMS) and projected decline in the temperature limitation of vegetation cover in the world's cold regions. The majority of ecosystems currently limited by temperature are expected to be primarily limited by other factors as soon as the latter half of this century.

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Plant Physiological Responses to Rising CO_2

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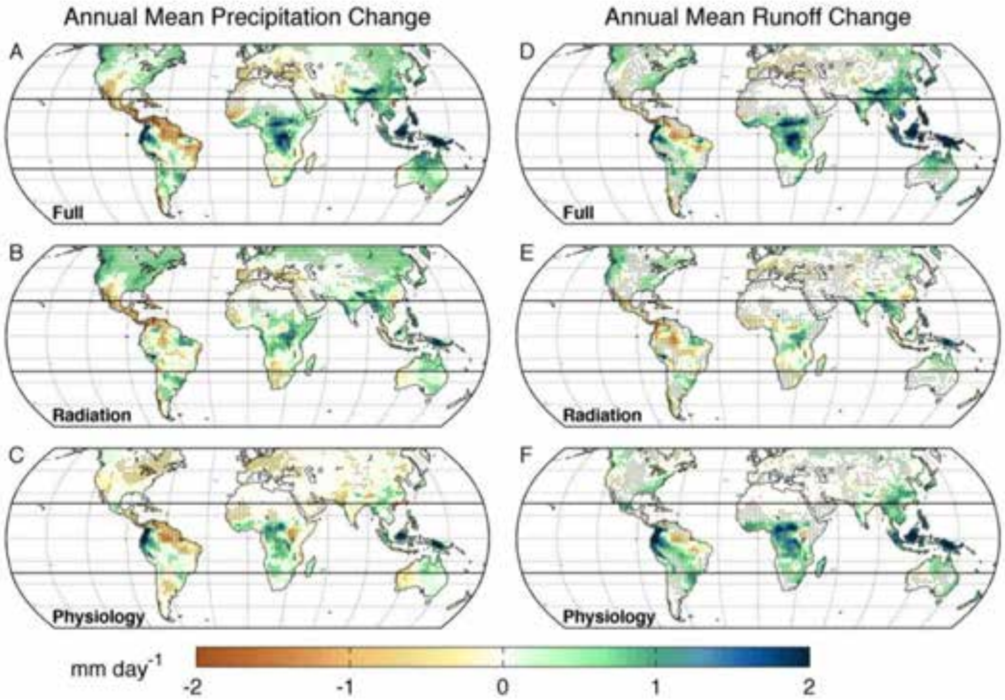
Plant-physiological responses to rising CO_2 increase tropical flood risk



- Assessments of future flood risk based only on precipitation changes ignore land processes
- Higher CO_2 may reduce stomatal conductance and transpiration
- We assessed relative impacts of plant-physiological and radiative- greenhouse effects on changes in daily runoff intensity over tropical continents using CESM
- Extreme percentile rates increase more than mean runoff
- Plant-physiological effects have a small impact on precipitation intensity, but are a dominant driver of runoff intensification

Kooperman, G. J., **M. D. Fowler**, **F. M. Hoffman**, **C. D. Koven**, K. Lindsay, M. S. Pritchard, A. L. S. Swann, and **J. T. Randerson** (2018), Plant-physiological responses to rising CO_2 modify simulated daily runoff intensity with implications for global-scale flood risk assessment, *Geophys. Res. Lett.*, 45(22):12,457–12,466. doi:10.1029/2018GL079901.

Marine Nutrient Constraints

Convergent Estimates of Marine Nitrogen Fixation

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Objective: To estimate global scale marine nitrogen (N_2) fixation, to probe possible mechanisms that control marine N_2 fixation, its links to carbon cycling, and to evaluate if the global, marine N cycle is at steady state over current era.

Approach: Analyze results of an inverse model that is constrained using global DIP, DIN, and DON data. Diagnose Community Earth System Model (CESMv2.0) simulation to find possible mechanisms. Independent models give similar results.

Results/Impacts: Nitrogen fixation and denitrification are spatially decoupled but nevertheless nitrogen sources and sinks appear to be balanced over the past few decades. A top down zooplankton grazing control is proposed as a key mechanism in shaping the global patterns of nitrogen fixation.

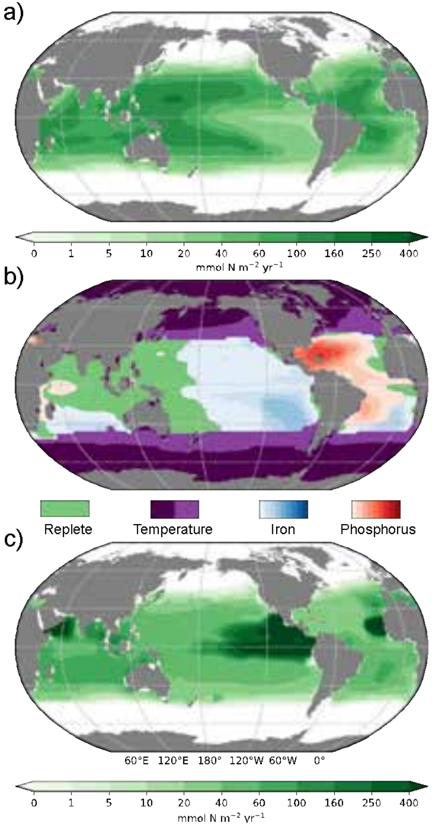

Figure: Prognostic model simulations of diazotrophs and N_2 fixation. Panel C has reduced grazing on the N fixing phytoplankton.

Wang, W.-L., **J. Keith Moore**, A. C. Martiny, and F. W. Primeau (2019), Convergent estimates of marine nitrogen fixation, *Nature*, 566(7743):205–211, doi:10.1038/s41586-019-0911-2.

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Biogeochemical and Hydrological Interactions

Soil moisture variability intensifies and prolongs eastern Amazon temperature and carbon cycle response to El Niño-Southern Oscillation

Objective: To understand how land–atmosphere coupling influences temperature and carbon cycle contrasts between El Niño and La Niña conditions in the Amazon.

Approach: Use the Energy Exascale Earth System Model (E3SM v0.3) to simulate land and atmosphere with observed SSTs during 1982–2016. Three simulations explored variability caused by full coupling (AMIP), sea surface temperatures only (SST_{var}), and soil moisture only (SM_{var}).

Results/Impacts: During the wet season (January–March), the contrast between El Niño and La Niña is driven by coupled ocean–atmospheric teleconnections. Soil moisture anomalies persist into the subsequent dry season in the eastern Amazon, strengthening and extending temperature and carbon cycle responses to forcing by ENSO.

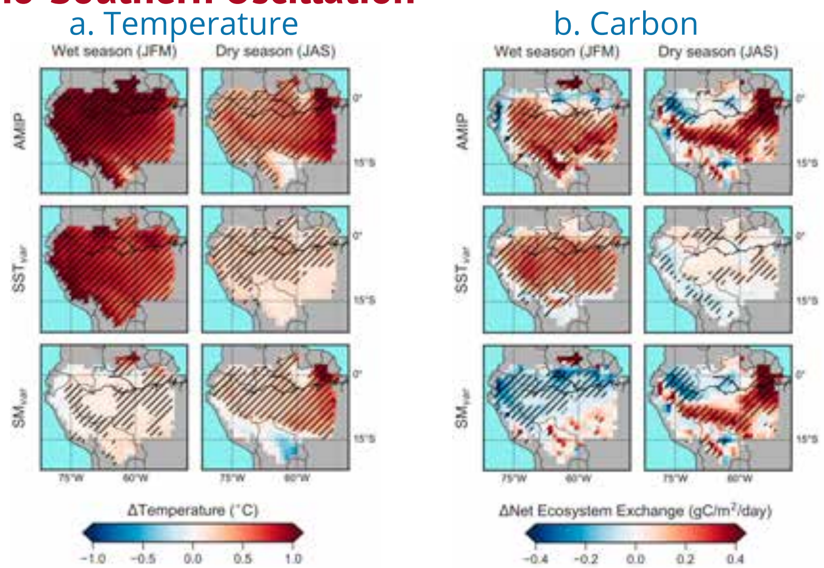

Figure: a. The difference between the mean temperature anomalies of El Niño years and those of La Niña years. Monthly anomalies are averaged across the wet season (JFM, left column) and dry season (JAS, right column). Each experiment (row) is described in the Approach section of the text. b. Same as a., but for monthly anomalies of net ecosystem exchange (positive is a flux to the atmosphere).

Levine, P. A., **J. T. Randerson**, **Y. Chen**, M. S. Pritchard, **M. Xu**, and **F. M. Hoffman** (2019), Soil moisture variability intensifies and prolongs eastern Amazon temperature and carbon cycle response to El Niño-Southern Oscillation, *J. Clim.*, 32(4):1273–1292, doi:10.1175/JCLI-D-18-0150.1.

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Coupled Model Intercomparison Project (CMIP6) Activities

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Los Alamos NATIONAL LABORATORY

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OAK RIDGE National Laboratory

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Simulation coordination with E3SM Project

Plans are to use the Compy cluster to conduct additional simulations

E3SM BGCv1 Simulation planning

Configuration	Experiment / CO2 coupling	Project	Intercomparison (if any)	Experiment name from intercomparison	Future pathway (if any)	Point of Contact	Preliminary or final case name (with link to Simulation page if applicable)	Initial condition case name	Initial condition date	Initial simulation year (forcings)	Final simulation year (forcings)	Soil nutrient mechanism	Ocn BGC on	Years of simulation required	Yea con
CTC-CNP	Spinup	E3SM	N/A	N/A	N/A	Xiaoying	20181115_BCRC_1850S	initialized from DECK spinup	TBD	1850	1850	CTC-CNP	TRUE	679	
	BDRD	E3SM	C4MIP / CMIP6 historical	historical	SSP5-8.5	Xiaoying	BDRD	20181115_BCRC_1850SPINU	TBD	1850	2100	CTC-CNP	TRUE	250	
	CNTL	E3SM	C4MIP / DECK	piControl	N/A	Xiaoying	CNTL	20181115_BCRC_1850SPINU	TBD	1850	1850	CTC-CNP	TRUE	250	
	BDRC	E3SM	C4MIP (Tier 2)	hist-bgc	SSP5-8.5	Mat	BDRC	20181115_BCRC_1850SPINU	TBD	1850	2100	CTC-CNP	TRUE	250	
	BCRC	E3SM	N/A	N/A	SSP5-8.5	Mat	BCRC	20181115_BCRC_1850SPINU	TBD	1850	2100	CTC-CNP	TRUE	250	
	BCRD	E3SM	N/A	N/A	SSP5-8.5	Xiaoying	BCRD	20181115_BCRC_1850SPINU	TBD	1850	2100	CTC-CNP	TRUE	250	
	1%CO2+BDRC	RUBISCO	C4MIP (Tier 1)	1pctCO2-bgc	N/A		BDRC_RCO2	20181115_BCRC_1850SPINU	TBD	1850	1850	CTC-CNP	TRUE	140	
	1%CO2+BCRD	RUBISCO	C4MIP (Tier 2)	1pctCO2-rad	N/A		BCRD_RCO2	20181115_BCRC_1850SPINU	TBD	1850	1850	CTC-CNP	TRUE	140	
	1%CO2+BDRD	E3SM	C4MIP / DECK	1pctCO2	N/A		BDRD_RCO2	20181115_BCRC_1850SPINU	TBD	1850	1850	CTC-CNP	TRUE	140	
	1%CO2+BDRC+Ndep	RUBISCO	C4MIP (Tier 2)	1pctCO2Ndep-bgc	N/A		BDRC_RCO2_NDep	20181115_BCRC_1850SPINU	TBD	1850	1850	CTC-CNP	TRUE	140	
	1%CO2+BCRD+Ndep	E3SM	N/A	N/A	N/A		BCRD_RCO2_NDep	20181115_BCRC_1850SPINU	TBD	1850	1850	CTC-CNP	TRUE	140	
	1%CO2+BDRD+Ndep	E3SM	C4MIP (Tier 2)	1pctCO2Ndep	N/A		BDRD_RCO2_NDep	20181115_BCRC_1850SPINU	TBD	1850	1850	CTC-CNP	TRUE	140	
	BDRC+8.5ext	E3SM	C4MIP (Tier 2)	ssp585-bgc, ssp585-bgcExt	SSP5-8.5ext		BDRC_8.5ext	BDRC	TBD	2100	2300	CTC-CNP	TRUE	200	
	BCRD+8.5ext	RUBISCO	N/A	N/A	SSP5-8.5ext		BCRD_8.5ext	BCRD	TBD	2100	2300	CTC-CNP	TRUE	200	
	BDRD+8.5ext	E3SM	C4MIP / ScenarioMIP	ssp585, ssp585ext	SSP5-8.5ext		BDRD_8.5ext	BDRD	TBD	2100	2300	CTC-CNP	TRUE	200	
	BDRC+3.4ext - overshoot only	E3SM	C4MIP (Tier 2)	ssp534-over, ssp534-over -ext	SSP5-3.4, SSP5-3.4ext		BDRC_3.4	BDRC	TBD	2040	2300	CTC-CNP	TRUE	260	
	BCRD+3.4ext	RUBISCO	N/A	N/A	SSP5-3.4, SSP5-3.4ext		BCRD_3.4	BCRD	TBD	2040	2300	CTC-CNP	TRUE	85	
	BDRD+3.4ext	E3SM	C4MIP / ScenarioMIP	ssp534-over, ssp534-over -ext	SSP5-3.4, SSP5-3.4ext		BDRD_3.4	BDRD	TBD	2040	2300	CTC-CNP	TRUE	260	
	4xCO2+BCRC	RUBISCO	N/A	N/A	N/A		BCRC_4XCO2	20181115_BCRC_1850SPINU	TBD	1850	1850	CTC-CNP	TRUE	150	
	4xCO2+BDRC	RUBISCO	N/A	N/A	N/A		BDRC_4XCO2	20181115_BCRC_1850SPINU	TBD	1850	1850	CTC-CNP	TRUE	150	
	4xCO2+BCRD	RUBISCO	N/A	N/A	N/A		BCRD_4XCO2	20181115_BCRC_1850SPINU	TBD	1850	1850	CTC-CNP	TRUE	150	
	4xCO2+BDRD	RUBISCO	N/A	N/A	N/A		BDRD_4XCO2	20181115_BCRC_1850SPINU	TBD	1850	1850	CTC-CNP	TRUE	150	
	LU_Deforestation	RUBISCO	LUMIP	deforest-glob			LU_DEFOREST		TBD	1850	1850	CTC-CNP	FALSE	80	
	Hist_NoLU	RUBISCO	LUMIP	hist_noLu			HIST_NOLU		TBD	1850	2014	CTC-CNP	FALSE	165	
	LU_Policy+7.0-2.6LU	RUBISCO	LUMIP	ssp370-ssp126Lu			LU_POLICY_7.0_2.6LU		TBD	2015	2100	CTC-CNP	FALSE	86	
	LU_Policy+2.6-7.0LU	RUBISCO	LUMIP	ssp126-ssp370Lu			LU_POLICY_2.6_7.0LU		TBD	2015	2100	CTC-CNP	FALSE	86	
CTC+Ocn-EF	Spinup	E3SM	N/A	N/A	N/A		BPRP_SPINUP	initialized from CTC-CNP spinup	TBD	1850	1850	CTC-CNP	TRUE	600	
	CNTL	E3SM	C4MIP / DECK	esm-piControl	N/A		BPRP_1850_CNTL	BPRP_SPINUP	TBD	1850	1850	CTC-CNP	TRUE	250	

Simulation table · Simulation progress chart

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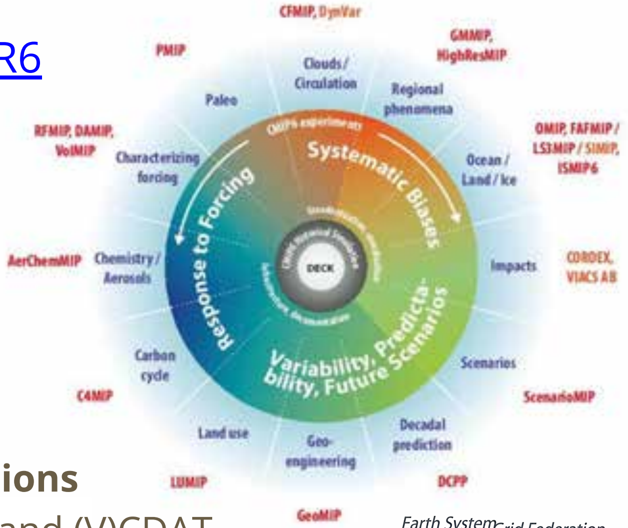
Coupled Model Intercomparison Project

WCRP World Climate Research Programme CMIP6

- For citation in the **IPCC Sixth Assessment Report** (AR6 WG1 Schedule), CMIP6 analysis papers must be
  - Submitted by December 31, 2019
  - Accepted by September 30, 2020
- To support RGMA scientists doing multi-model research and benchmarking, **BER RGMA** & **Data Programs** are coordinating & sponsoring
  - Staging **CMIP6 output from ESGF** plus **reanalysis** & **observations**
  - Series of **tutorials** on CMIP6 organization, Jupyter notebooks, and (V)CDAT
  - **RGMA CMIP6 Hackathon** via videoconferencing at multiple hubs
- Lab & university researchers are co-organizing activities
  - *Forrest Hoffman (ORNL, RUBISCO), Jialin Liu (NERSC), Paul Ullrich (UC Davis, HYPERFACETS), Michael Wehner (LBNL, CASCADE), Wilbert Weijer (LANL, HiLAT)*
- **NERSC: 2¼ PB disk storage** & **interactive computing resources**
  - *Richard Gerber, Rollin Thomas, Jialin Liu*



Earth System Grid Federation ESGF

NERSC

jupyterhub

/global/cscratch1/sd/cmip6

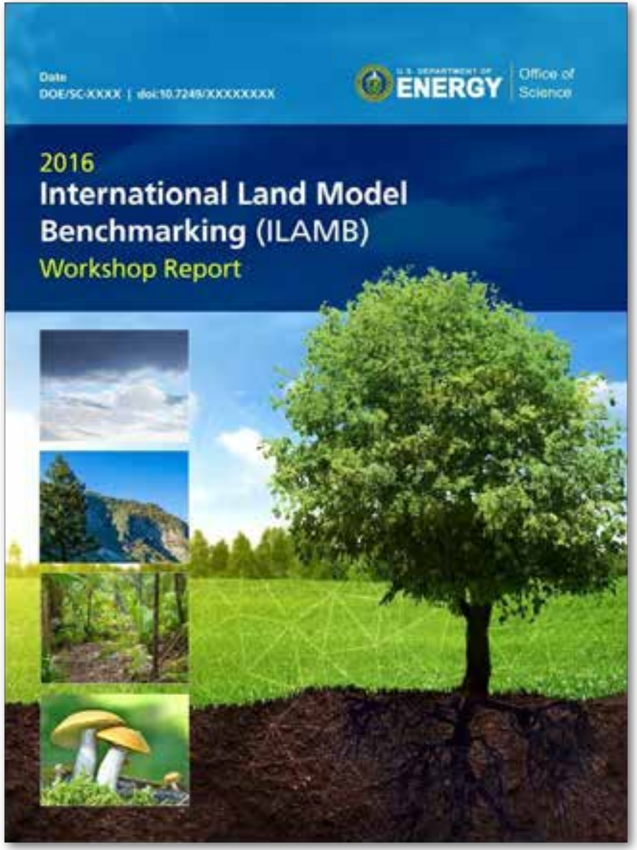
International Land Model Benchmarking (ILAMB) Development

- **First ILAMB Workshop** was held in Exeter, UK, on June 22–24, 2009
- **Second ILAMB Workshop** was held in Irvine, CA, USA, on January 24–26, 2011
    - ~45 researchers participated from the US, Canada, UK, Netherlands, France, Germany, Switzerland, China, Japan, and Australia
    - Developed methodology for model-data comparison and baseline standard for performance of land model process representations (Luo et al., 2012)

2016 International Land Model Benchmarking (ILAMB) Workshop
May 16–18, 2016, Washington, DC

Third ILAMB Workshop was held May 16–18, 2016

- Workshop Goals
  - Design of new metrics for model benchmarking
  - Model Intercomparison Project (MIP) evaluation needs
  - Model development, testbeds, and workflow processes
  - Observational data sets and needed measurements
- Workshop Attendance
  - 60+ participants from Australia, Japan, China, Germany, Sweden, Netherlands, UK, and US (10 modeling centers)
  - ~25 remote attendees at any time



Hoffman et al. (2017)

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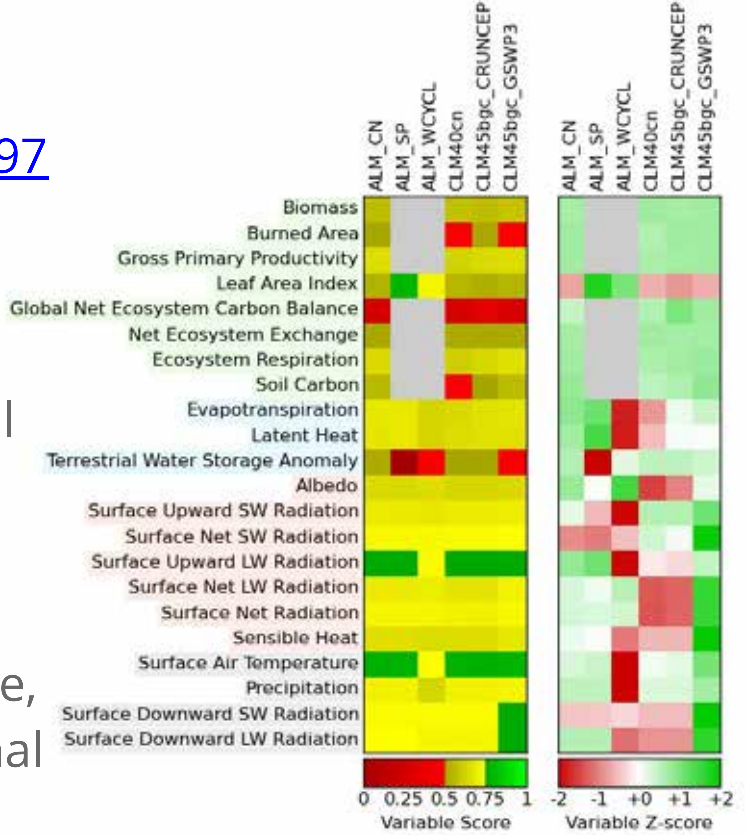
Development of ILAMB Packages

- **ILAMBv1** released at 2015 AGU Fall Meeting Town Hall, doi:[10.18139/ILAMB.v001.00/1251597](https://doi.org/10.18139/ILAMB.v001.00/1251597)
- **ILAMBv2** released at 2016 ILAMB Workshop, doi:[10.18139/ILAMB.v002.00/1251621](https://doi.org/10.18139/ILAMB.v002.00/1251621)
- Open Source software freely distributed
- Routinely used for E3SM and CESM Land Model evaluation during development
- Employed to evaluate CMIP5 models
- Models are scored based on statistical comparisons (bias, RMS error, phase, amplitude, spatial distribution, Taylor scores) and functional response metrics



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ILAMB package provides rigorous model benchmarking capabilities

Objective: To provide a platform for objectively and systematically benchmarking terrestrial biogeochemistry & land surface models.

Approach: We developed an open source benchmarking software package that generates graphical diagnostics and scores model performance based on comparisons with observational data.

Results/Impacts: We used a suite of in situ, remote sensing, and reanalysis data sets in a Python package developed to evaluate model fidelity. Described is the benchmarking philosophy and mathematical methodology embodied in the ILAMB package, which is already in use in international modeling centers.

Collier, N., **F. M. Hoffman**, **D. M. Lawrence**, **G. Keppel-Aleks**, **C. D. Koven**, **W. J. Riley**, **M. Mu**, **J. T. Randerson** (2018), The International Land Model Benchmarking (ILAMB) System: Design, Theory, and Implementation, *J. Adv. Model. Earth Sy.*, 10(11):2731–2754, doi:10.1029/2018MS001354.

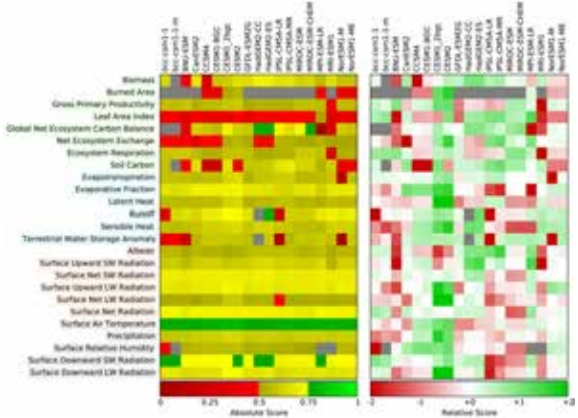


Figure: ILAMB scores land models (columns) across a variety of variables (rows).

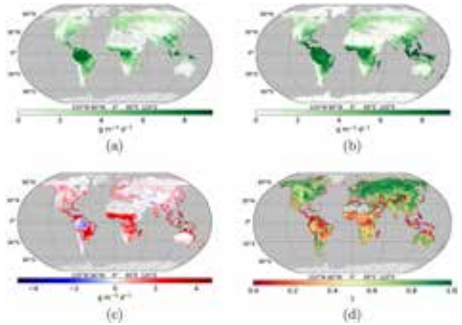


Figure: Example model–data comparison for gross primary production (GPP).

ILAMBv2.4 Package Current Variables

- **Biogeochemistry:** Biomass (Contiguous US, Pan Tropical Forest), Burned area (GFED3), CO_2 (NOAA GMD, Mauna Loa), Gross primary production (Fluxnet, GBAF), Leaf area index (AVHRR, MODIS), Global net ecosystem carbon balance (GCP, Khatiwala/Hoffman), Net ecosystem exchange (Fluxnet, GBAF), Ecosystem Respiration (Fluxnet, GBAF), Soil C (HWSD, NCSCDv22, Koven)
- **Hydrology:** Evapotranspiration (GLEAM, MODIS), Evaporative fraction (GBAF), Latent heat (Fluxnet, GBAF, DOLCE), Runoff (Dai, LORA), Sensible heat (Fluxnet, GBAF), Terrestrial water storage anomaly (GRACE), Permafrost (NSIDC)
- **Energy:** Albedo (CERES, GEWEX.SRB), Surface upward and net SW/LW radiation (CERES, GEWEX.SRB, WRMC.BSRN), Surface net radiation (CERES, Fluxnet, GEWEX.SRB, WRMC.BSRN)
- **Forcing:** Surface air temperature (CRU, Fluxnet), Diurnal max/min/range temperature (CRU), Precipitation (CMAP, Fluxnet, GPCC, GPCP2), Surface relative humidity (ERA), Surface down SW/LW radiation (CERES, Fluxnet, GEWEX.SRB, WRMC.BSRN)

ILAMB Used to Evaluate ELM

- **ILAMB** was used to continuously evaluate ELM performance during development
- Zhu et al. (2019) paper describes new nitrogen, phosphorus, and carbon interactions in the **E3SM Land Model (ELM)**
- The majority of figures in the paper highlighted ILAMB benchmarking results as compared with prior versions of CLM

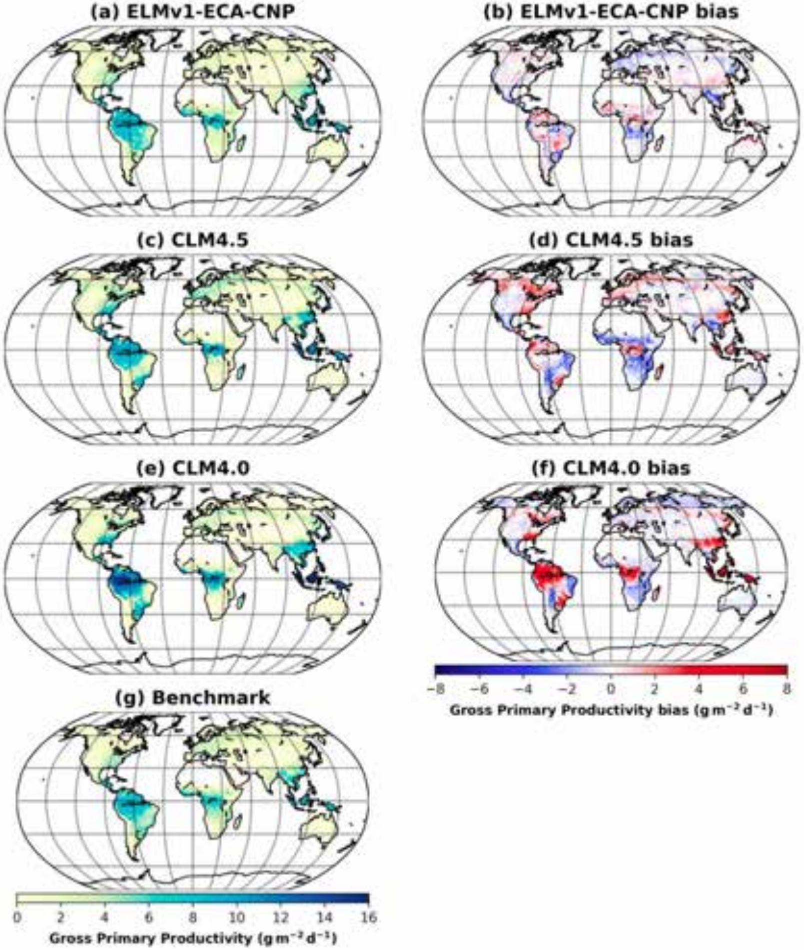
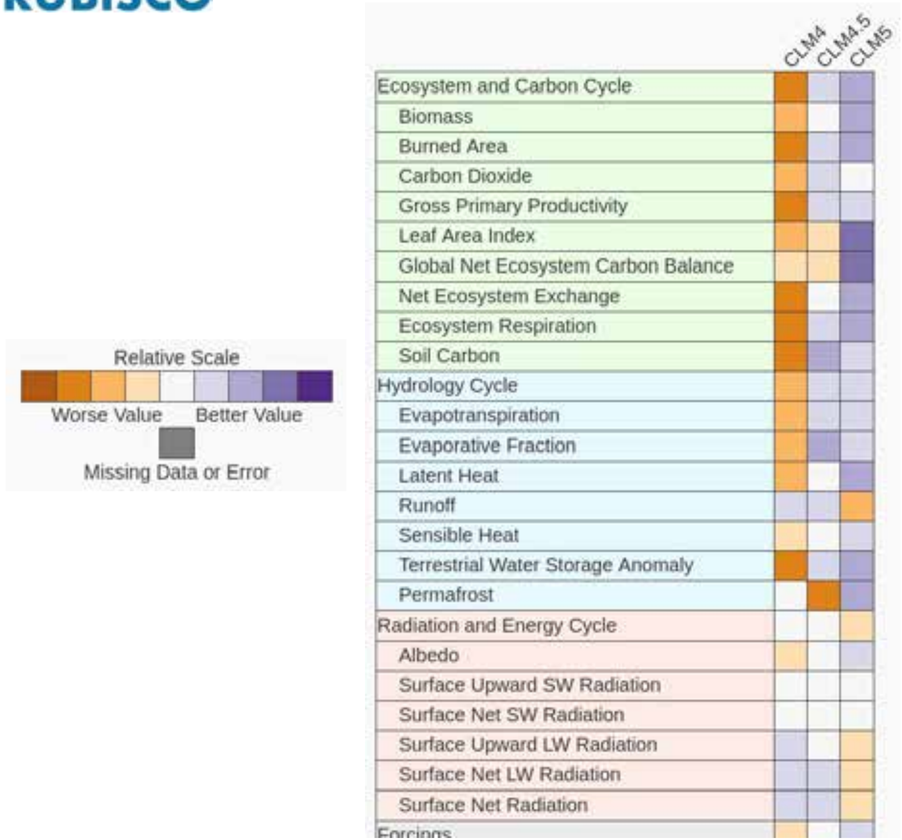


Figure: Global patterns of mean gross primary productivity and bias (model-benchmark) using the International Land Model Benchmarking (ILAMB) package. Energy Exascale Earth System Model (E3SM) Land Model version 1-equilibrium chemistry approximation (ELMv1-ECA) and Community Land Model version 4.5 (CLM4.5) performed generally better than CLM4.0, particularly over the tropical forest region.

ILAMB Assessing Several Generations of CLM

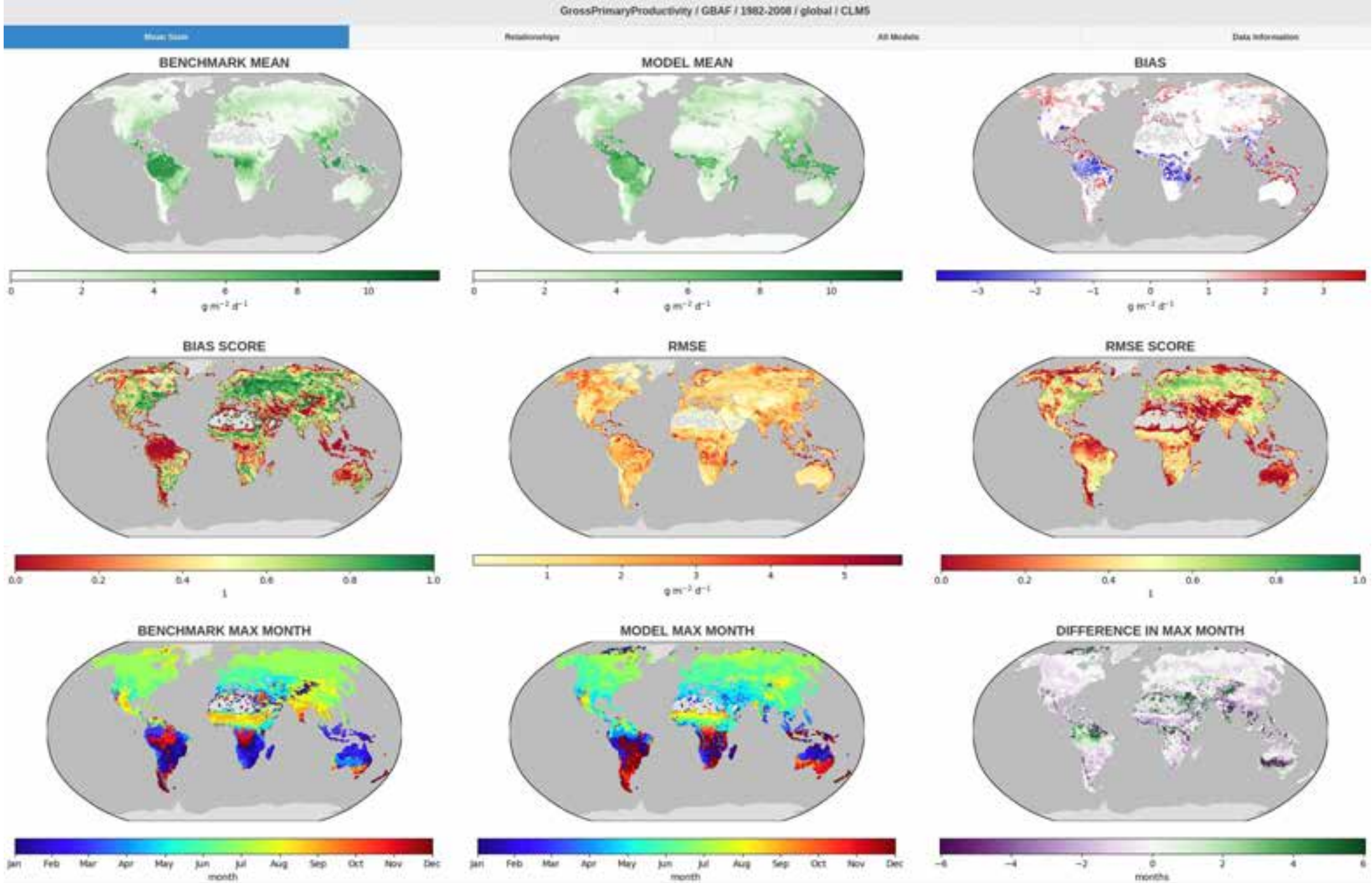


- Improvements in mechanistic treatment of hydrology, ecology, and land use with many more moving parts
- Simulation improved even with enhanced complexity
- Observational datasets not always self-consistent
- Forcing uncertainty confounds assessment of model development (not shown)

http://webext.cgd.ucar.edu/I20TR/_build_set1F/

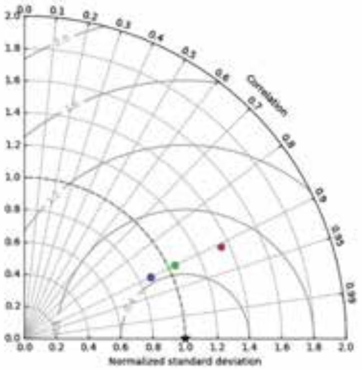
(Lawrence et al., in press)

ILAMB Graphical Diagnostics

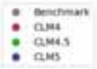


ILAMB Graphical Diagnostics

SPATIAL TAYLOR DIAGRAM



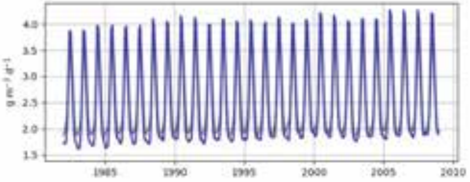
MODEL COLORS



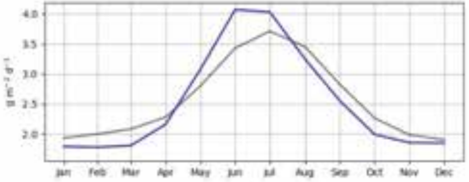
Spatially integrated regional mean

MODEL COLORS

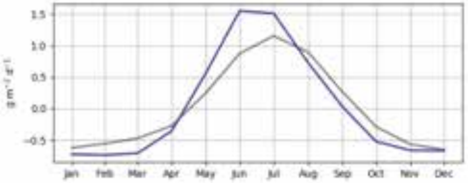
REGIONAL MEAN



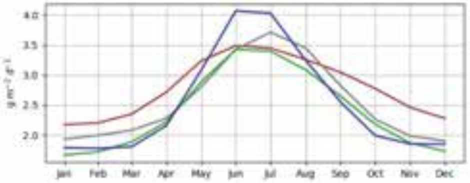
ANNUAL CYCLE



MONTHLY ANOMALY



ANNUAL CYCLE



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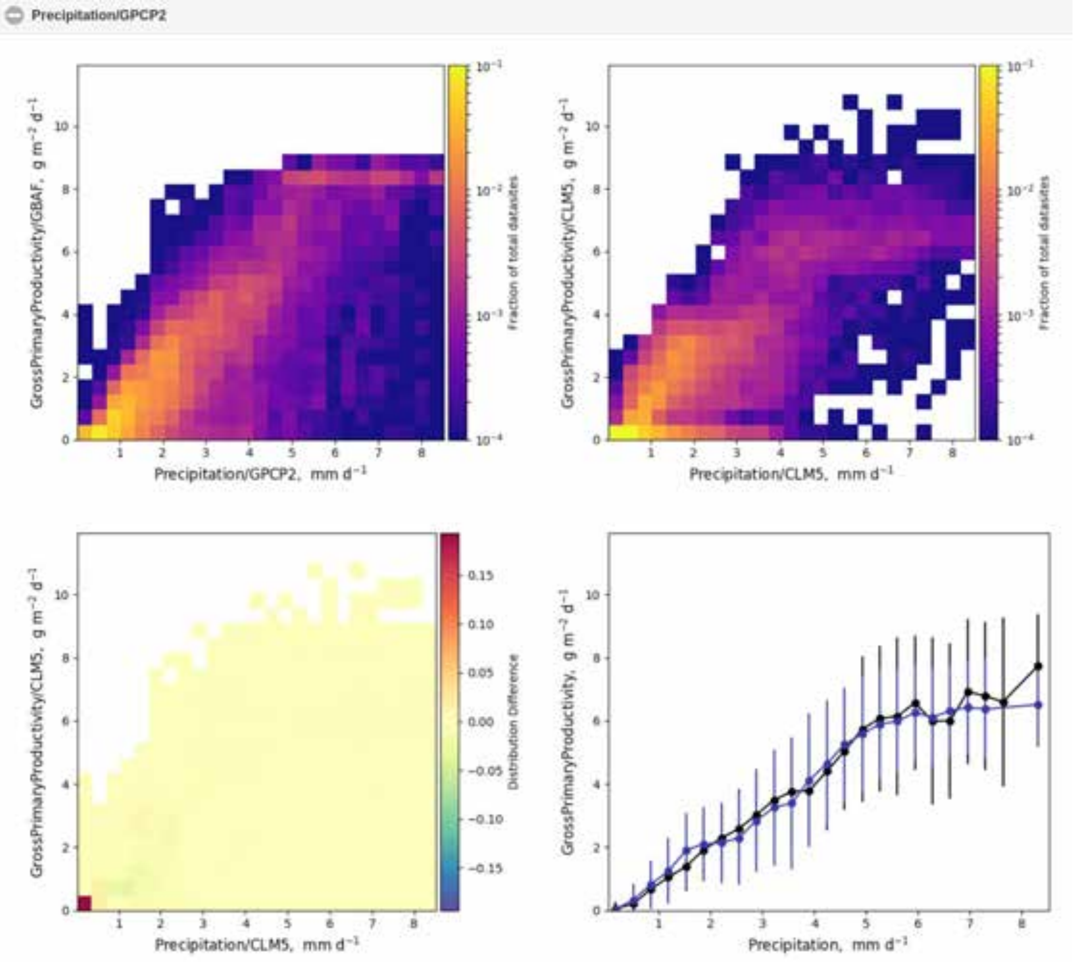
Variable-to-Variable Comparisons



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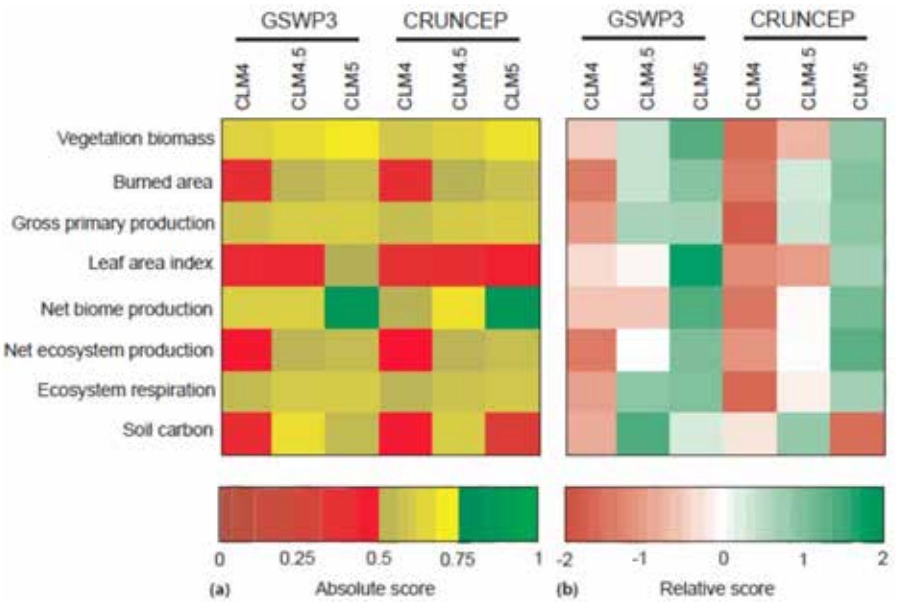
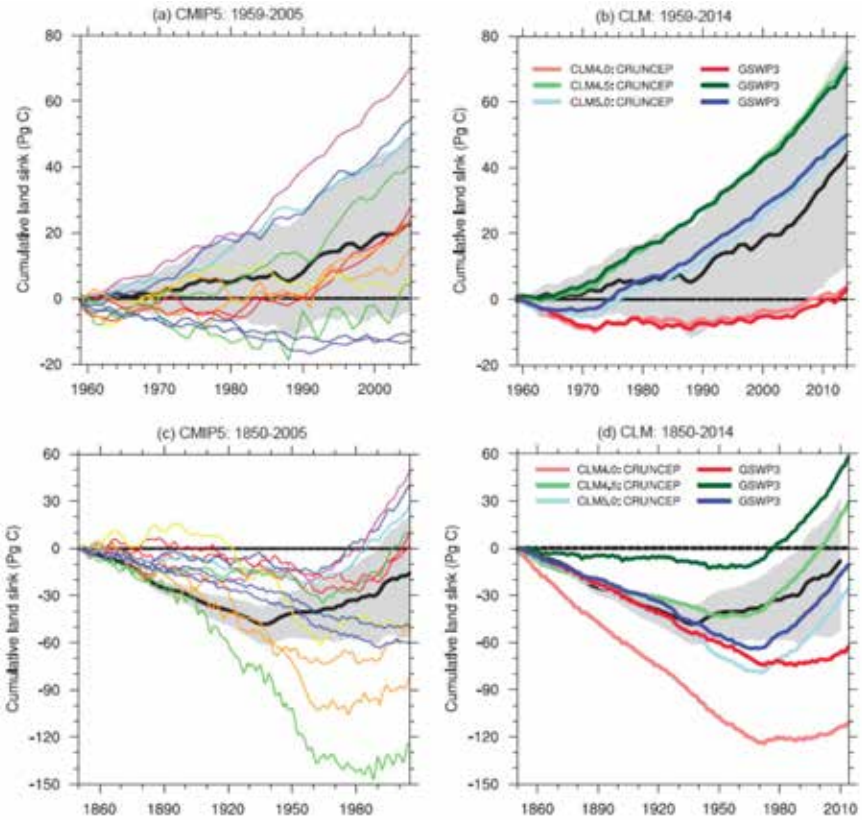
Land Model Performance Depends Strongly on Forcing





ILAMB performance for CLM4, CLM4.5, and CLM5 forced with GSWP3 vs. CRUNCEP (left) and the cumulative land carbon sink for CMIP5 vs. CLM offline models (right).

Bonan et al. (2019)

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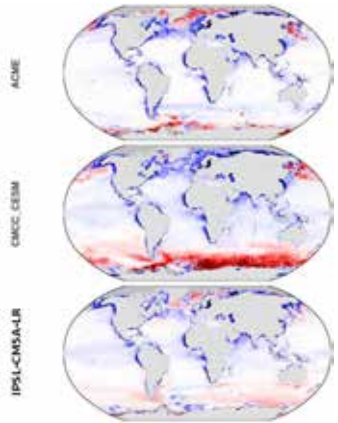
International Ocean Model Benchmarking (IOMB) Package

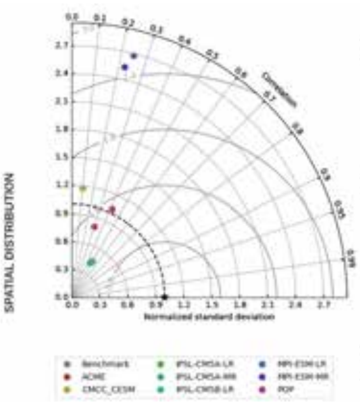
- Evaluates ocean biogeochemistry results compared with observations (global, point, ship tracks)
- Scores model performance across a wide range of independent benchmark data
- Leverages ILAMB code base, also runs in parallel
- Built on python and open standards
- Is also open source and will be released soon

Chlorophyll / SeaWIFS

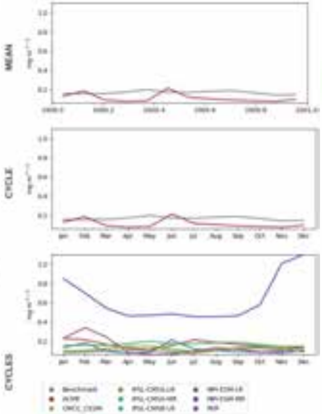
Bias

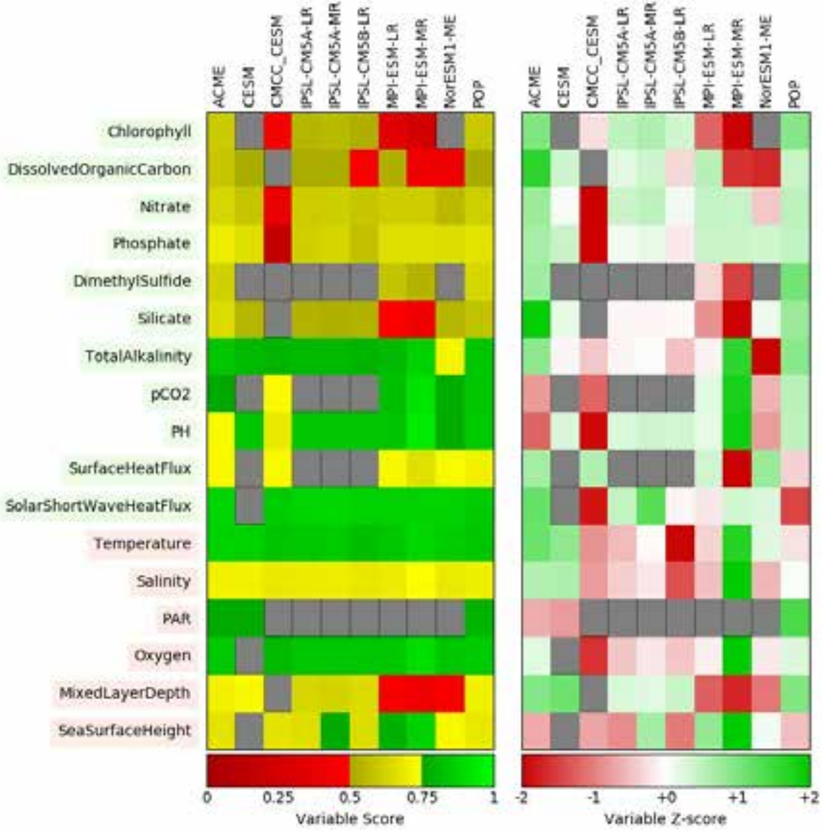


Spatial Distribution



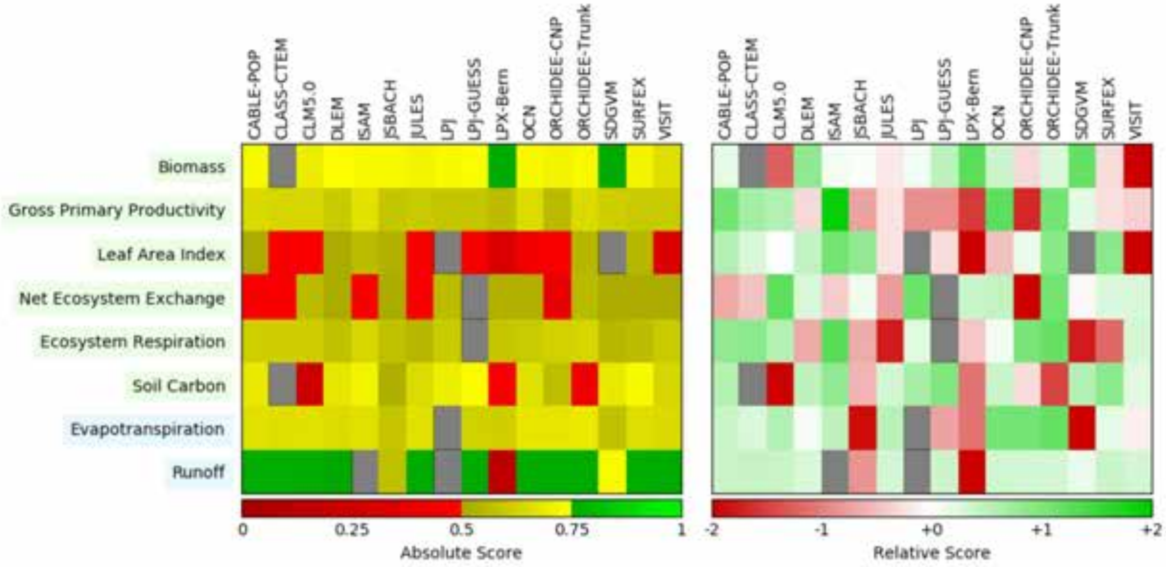
Annual & Seasonal Cycles





Global Carbon Budget 2018 - TRENDY Models

Evaluation of the TRENDY DGVMs using the International Land Model Benchmarking system (ILAMB; Collier et al., 2018) (left) absolute skill scores and (right) skill scores relative to other models for a subset of ILAMB variables.



Le Quéré et al. (2018)

CMIP5 vs. CMIP6 Land Models

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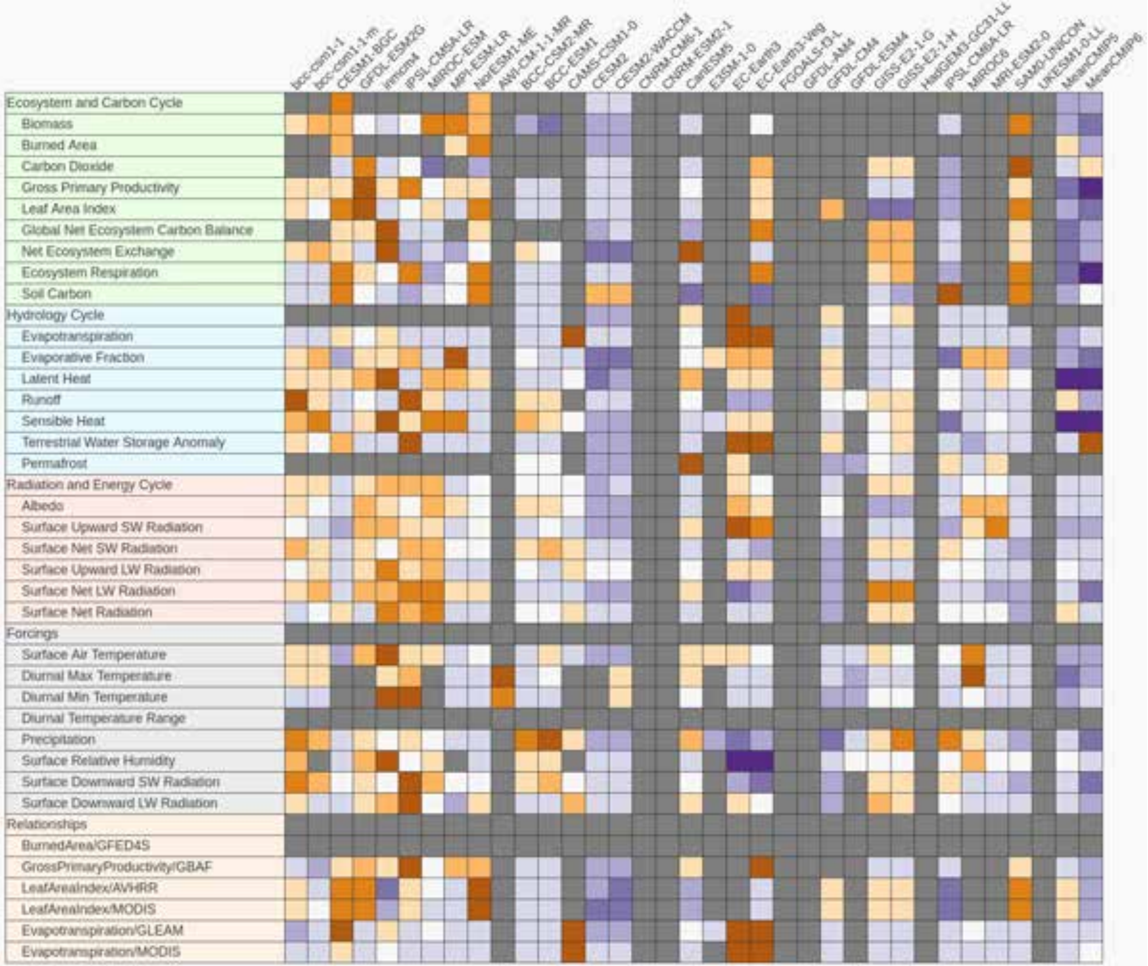
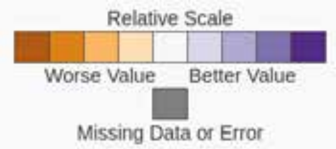
- The CMIP6 suite of land models (right) has improved over the CMIP5 suite of land models (left)
- The multi-model mean outperforms any single model for each suite of models
- The multi-model mean CMIP6 land model is the “best” model overall





(Hoffman et al., in prep)

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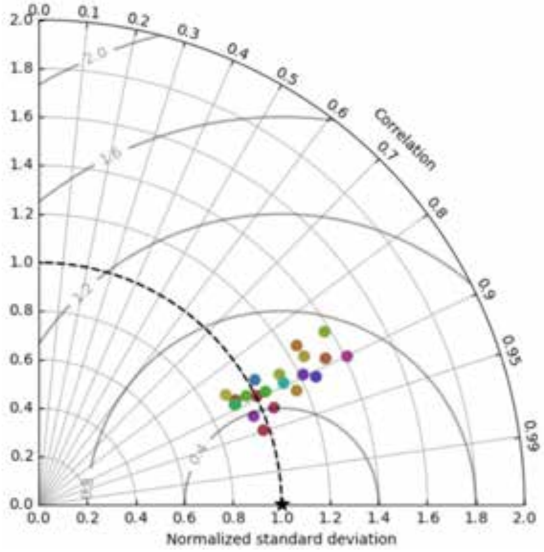
Gross Primary Productivity

	Download Data	Period Mean (original grids) [Pg yr-1]	Model Period Mean (intersection) [Pg yr-1]	Model Period Mean (complement) [Pg yr-1]	Benchmark Period Mean (intersection) [Pg yr-1]	Benchmark Period Mean (complement) [Pg yr-1]	Bias [g m-2 d-1]	RMSE [g m-2 d-1]	Phase Shift [months]	Bias Score [1]	RMSE Score [1]	Seasonal Cycle Score [1]	Spatial Distribution Score [1]	Overall Score [1]
Benchmark	[-]	118.												
bcc-csm1-1	[-]	123.	114.	6.80	118.	0.0600	0.203	1.94	1.27	0.424	0.287	[illegible]	0.946	0.543
bcc-csm1-1-m	[-]	112.	108.	4.10	118.	0.501	-0.116	1.94	1.38	0.413	0.265	0.794	0.934	0.534
BCC-CSM2-MR	[-]	123.	115.	8.31	118.	0.501	-0.0721	1.68	1.28	0.433	0.326	0.796	0.941	0.564
BCC-ESM1	[-]	157.	133.	21.4	118.	0.0640	0.325	1.84	1.23	0.429	0.302	[illegible]	0.945	0.557
CanESM5	[-]	141.	131.	8.05	118.		0.675	1.85	1.70	0.427	0.330	[illegible]	0.934	0.544
CESM1-BGC	[-]	129.	124.	4.32	118.	0.501	0.309	1.74	1.38	0.392	0.350	0.761	[illegible]	0.545
CESM2	[-]	110.	105.	4.21	118.	0.473	-0.0938	1.72	1.52	0.411	0.364	0.786	0.935	0.572
CESM2-WACCM	[-]	110.	106.	4.28	118.	0.473	-0.0889	1.73	1.50	0.410	0.364	0.788	0.936	0.572
EC-Earth3-Veg	[-]	136.	134.	2.52	118.		0.330	1.99	1.49	0.417	0.312	0.755	0.931	0.545
GFDL-ESM2G	[-]	167.	155.	9.78	118.		1.19	3.18	1.45	0.360	[illegible]	[illegible]	0.880	[illegible]
GISS-E2-1-G	[-]	133.	118.	12.6	117.	1.29	0.0302	1.55	1.23	0.411	0.355	0.741	0.905	0.553
GISS-E2-1-H	[-]	131.	116.	13.8	118.	0.654	-0.0269	1.57	1.19	0.400	0.353	0.760	0.913	0.556
inmcm4	[-]	136.	128.	8.25	113.	5.44	0.351	1.78	1.41	0.451	0.308	0.766	0.935	0.554
IPSL-CM5A-LR	[-]	165.	153.	9.00	118.	0.347	1.10	2.73	1.30	[illegible]	[illegible]	0.770	0.889	[illegible]
IPSL-CM6A-LR	[-]	116.	111.	4.25	118.	0.486	0.0566	1.45	1.32	[illegible]	0.364	0.751	0.960	0.587
MeanCMIP5	[-]	138.	131.	6.75	118.		0.561	1.44	1.13	0.462	[illegible]	0.794	0.959	[illegible]
MeanCMIP6	[-]	121.	116.	5.10	118.		0.159	1.10	1.12	[illegible]	[illegible]	0.796	[illegible]	[illegible]
MIROC-ESM	[-]	129.	121.	6.01	108.	10.1	0.308	2.06	1.40	0.425	0.322	0.749	0.918	0.547
MPI-ESM-LR	[-]	170.	162.	6.90	110.	8.62	1.22	2.37	1.43	0.378	0.291	[illegible]	0.926	0.517
NorESM1-ME	[-]	129.	121.	6.29	118.		0.331	1.92	1.46	[illegible]	0.350	0.759	[illegible]	0.530
SAM0-UNICON	[-]	131.	126.	4.95	118.	0.501	0.371	1.75	1.39	0.398	0.338	0.764	[illegible]	0.537

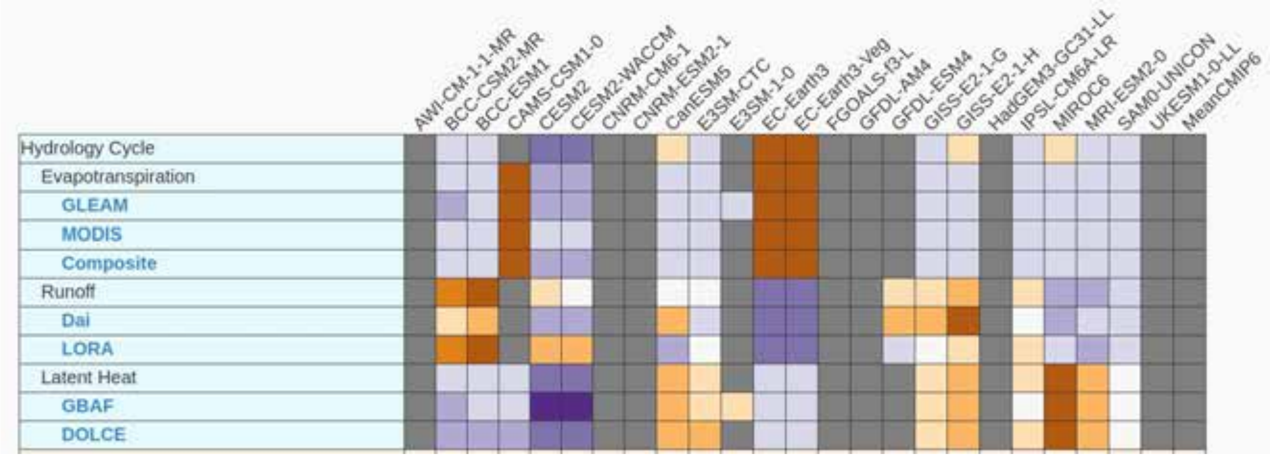
- Multimodel GPP is compared with global seasonal GBAF estimates
- We can see Improvements across generations of models (e.g., CESM1 vs. CESM2, IPSL-CM5A vs. 6A)
- The mean CMIP6 and CMIP5 models perform best

Spatial Taylor Diagram



Addressing Observational Uncertainty in ILAMB

- Few observational datasets provide complete uncertainties
- ILAMB uses multiple datasets for most variables and allows users to weight them according to a rubric of uncertainty, scale mismatch, etc.
- ILAMB can also use:
  - Full spatial/temporal uncertainties provided with the data
  - Fixed, expert-derived dataset uncertainty (e.g., 0.2 mm d^{-1})
  - Uncertainties derived by combining multiple datasets



Collaborative and Outreach Activities

Soil Carbon Dynamics Working Group

RUBISCO

U.S. DEPARTMENT OF ENERGY

- Formed after community recommendation from the 2016 International Land Model Benchmarking (ILAMB) Workshop Report
- Objective is to apply data and models to improve predictive understanding
- June and September conference calls led to meeting at ORNL in October

Data to Knowledge

Synthesize existing data from collaborative networks, archives, and publications

+

Knowledge to Data

Perform simulations to test hypotheses and characterize model structural uncertainties

→

Predictive Understanding

Design functional relationship metrics to confront models and apply data-driven approaches to model formulation

Global Data Synthesis Theme

- Combine field observations from collaborative sampling networks and databases, including International Soil Carbon Network (ISCN) and published literature
- Quantify vertical distribution of SOM and responses to controlling mechanisms

Model–Data Integration Theme

- Develop consistent datasets for initializing, forcing, and benchmarking microbially explicit soil carbon models
- Characterize model structural uncertainty through software frameworks to understand controlling mechanisms

For more information, contact Forrest M. Hoffman <forrest@climatemodeling.org> or Umakant Mishra <umishra@anl.gov>

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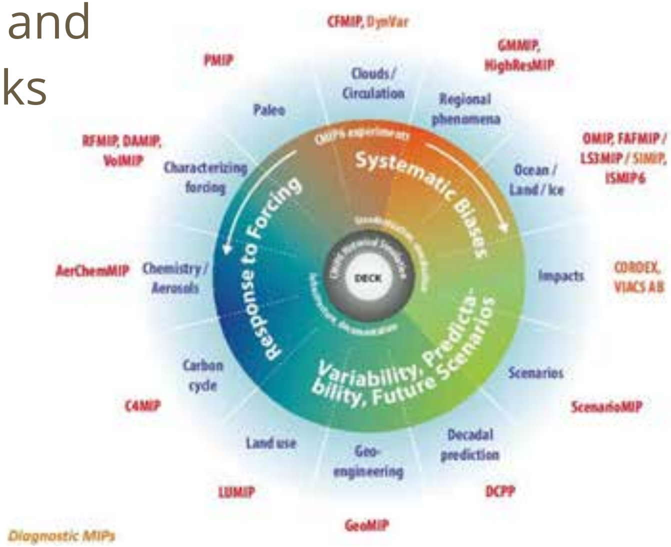
RUBISCO-AmeriFlux Working Group

- Formed after community recommendation from the 2016 International Land Model Benchmarking (ILAMB) Workshop Report
- Several conference calls have occurred, at least one more is scheduled, and **meeting scheduled for mid October**
- More than 40 scientists have registered to attend

- ***Multifactor*** ecosystem responses to climate change, extreme events, and changes in seasonality using e.g., Ameriflux, phenocam observations, remote sensing products, observations from citizen science programs, and others.
- Roles of ***extreme events*** and "return times" on ecosystem resilience.
- ***Long-term*** trends in light use efficiency, water use efficiency, evapotranspiration, and other quantities, some of which may yield new emergent constraints
- ***Advanced mathematical analyses*** of time series of ecosystem dynamics to infer underlying controls across temporal scales.
- Synthesizing ***new observations*** from data sets across spatial and temporal scales (e.g., AmeriFlux, remote sensing, disturbance maps, SIF, etc.)
- ***"Super site" benchmarks*** developed around stable, long-running flux tower sites with a diversity of collocated measurements (e.g., AmeriFlux, CZOs, LTER, NEON)
- ***Spatial scaling methods*** to interpret point measurements, incorporating ancillary databases, to study areas, regions, continents, and the globe.

RGMA CMIP6 Analysis and Hackathon

- Tutorials and “Office Hours” prior to the CMIP6 Hackathon
  - **CMIP6 Tutorial** - July 11 at 9am PDT / noon EDT (Wilbert Weijer, LANL, and Karl Taylor, PCMDI)
  - **Python and Jupyter at NERSC** - slides from New User Training (Rollin Thomas, NERSC)
  - **Office Hours** - July 17 at 9am PDT / noon EDT (Paul Durack, PCMDI, and Jialin Liu, NERSC)
  - **(V)CDAT Tutorial** - July 24 at 9am PDT / noon EDT (Charles Doutriaux, PCMDI)
- **Slack Workspace** for messaging questions, tips, and tricks
- **GitHub Repository** for collaborative development and sharing analysis code, scripts, and Jupyter notebooks
- **RGMA CMIP6 Hackathon**, July 31–August 6, 2019
  - RGMA researchers are encouraged to participate at one of the hubs at LANL, LBNL, ORNL, U. Washington, and PNNL
  - Tutorials will build capabilities among RGMA researchers
  - Pre-loaded data will allow scientists to focus on analysis
  - Event will foster cross-institution/project collaboration
  - Impact of analysis papers will be a measure of success
  - Final report on lessons learned from CMIP6 and format



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