Reducing Uncertainty in Biogeochemical Interactions Through Synthesis and Computation

Forrest M. Hoffman

Regional and Global Model Analysis (RGMA) PI Meeting
October 13, 2020

U.S. DEPARTMENT OF
ENERGY
Office of Science

RUBISCO

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

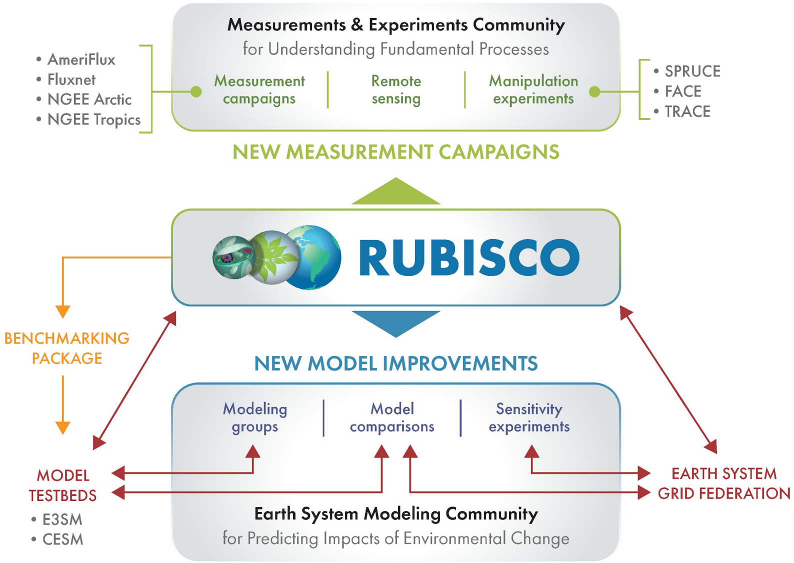
Forrest M. Hoffman (Laboratory Research Manager), William J. Riley (Senior Science Co-Lead), and James T. Randerson (Chief Scientist)

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

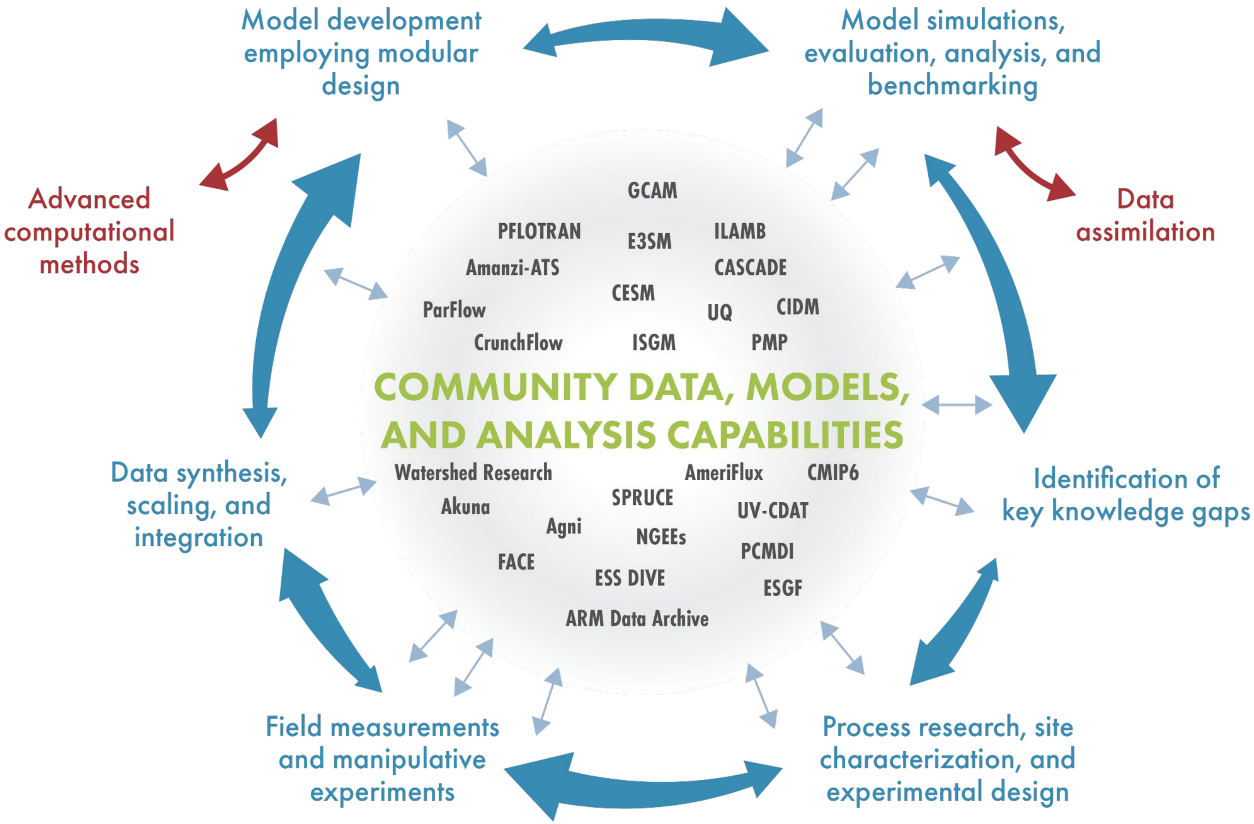
Research Objectives

- 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.

DOE's Model-Data-Experiment Enterprise



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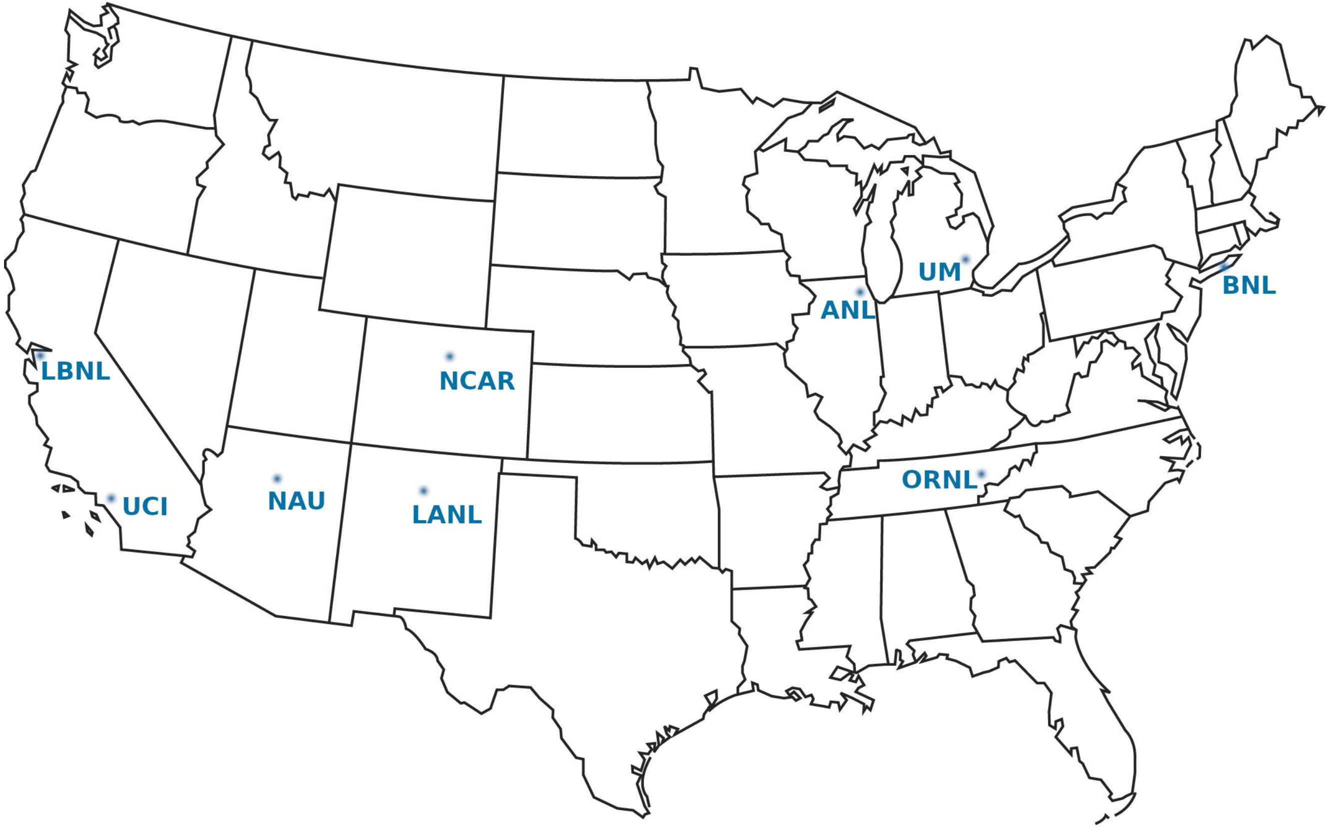
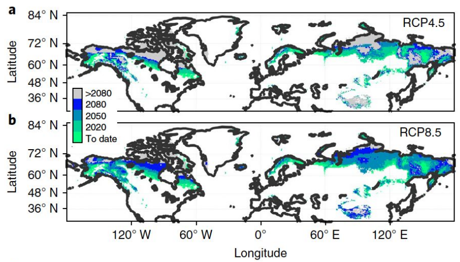
RUBISCO SFA Nine Partner Institutions

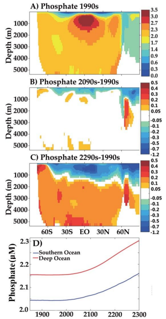
- **5 National Labs**
  - Argonne
  - Brookhaven
  - Los Alamos
  - Lawrence Berkeley
  - Oak Ridge
- **3 Universities**
  - UC Irvine
  - U. Michigan
  - N. Arizona U.
- **National Center for Atmospheric Research (NCAR)**

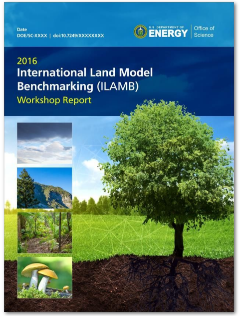


RUBISCO SFA Research and Development Activities

- 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 MIP activities
  - New high impact science on global biogeochemical cycles
  - Community engagement activities

RUBISCO SFA Accomplishments

- ILAMBv2 design paper in *JAMES* (Collier et al., 2018); IOMB paper in *Atmos.* (Ogunro et al., 2018)
- Systematic use of ILAMBv2 to develop and validate:
    - ELMv1 (Zhu et al., 2019; Burrows et al., 2020)
    - CLM5 (Bonan et al., 2019; Lawrence et al., 2019)
- Use of ILAMBv2 by the Global Carbon Project to evaluate TRENDY models (Le Quéré et al., 2018; Friedlingstein et al., 2019)
- ILAMBv2 is widely used by the international modeling community (MPI, Hadley Centre, Canadian Climate Centre, U. Tokyo, ...)
- ILAMBv2 and IOMB evaluation figures expected in Chapter 5 of IPCC AR6
- **We published 34 papers in CY2019** and **28 papers in CY2020 (so far)**
    - 3 *Science* series and 16 *Nature* series (2019–2020)
    - >10,000 cumulative citations

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

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.

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.

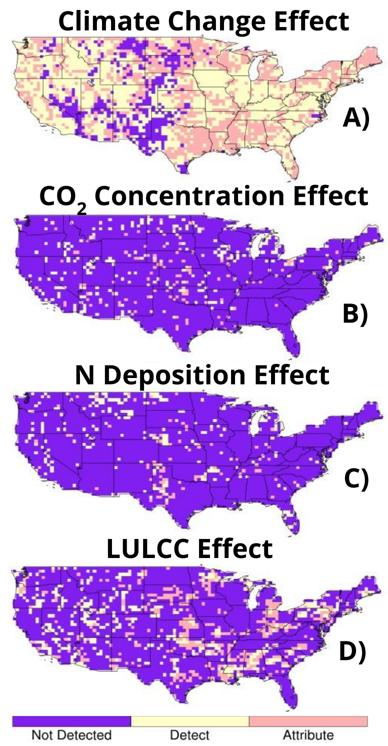

Figure: Spatial patterns of D&A scaling factors. Not detected (purple) denotes a scaling factor whose corresponding 95% confidence interval was less than zero or included zero. If the 95% confidence interval was greater than zero but did not include one, the forcing was detected (yellow). A positive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

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

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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.

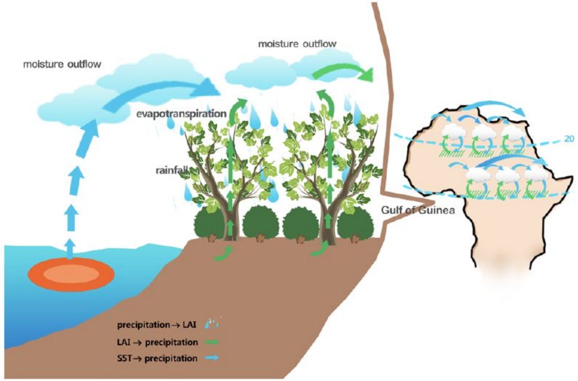

Figure: (a) Emergent benchmarks for West Sahel precipitation from observations and CMIP5 ESMs. (b) Percentage of model grid cells exhibiting interactions consistent with the observed mechanistic benchmark for West Sahel precipitation. SST, LAI, and P are sea surface temperature, leaf area index, and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

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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.

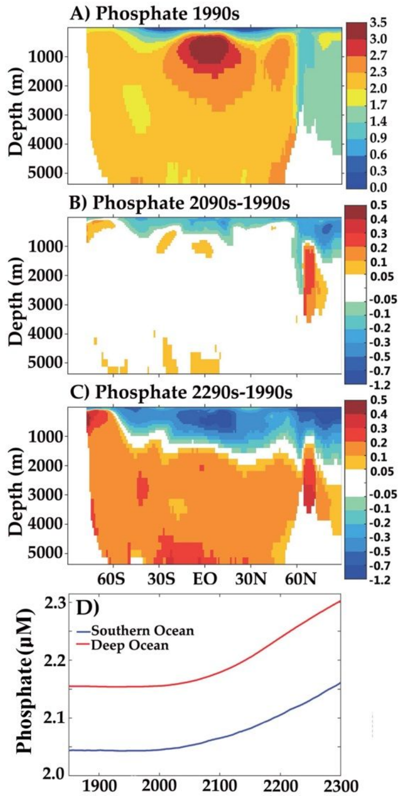

Figure: Antarctic trapping increases nutrient transfer to the deep ocean.

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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.

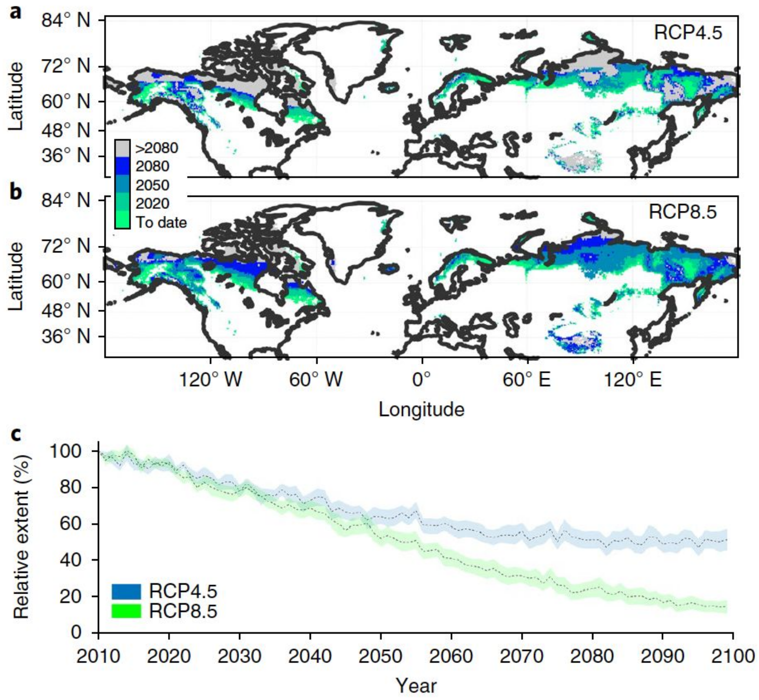

Figure: Observed (GIMMS) and projected decline in the temperature limitation of vegetation cover in the world's cold regions. The majority of ecosystems currently limited by temperature are expected to be primarily limited by other factors as soon as the latter half of this century.

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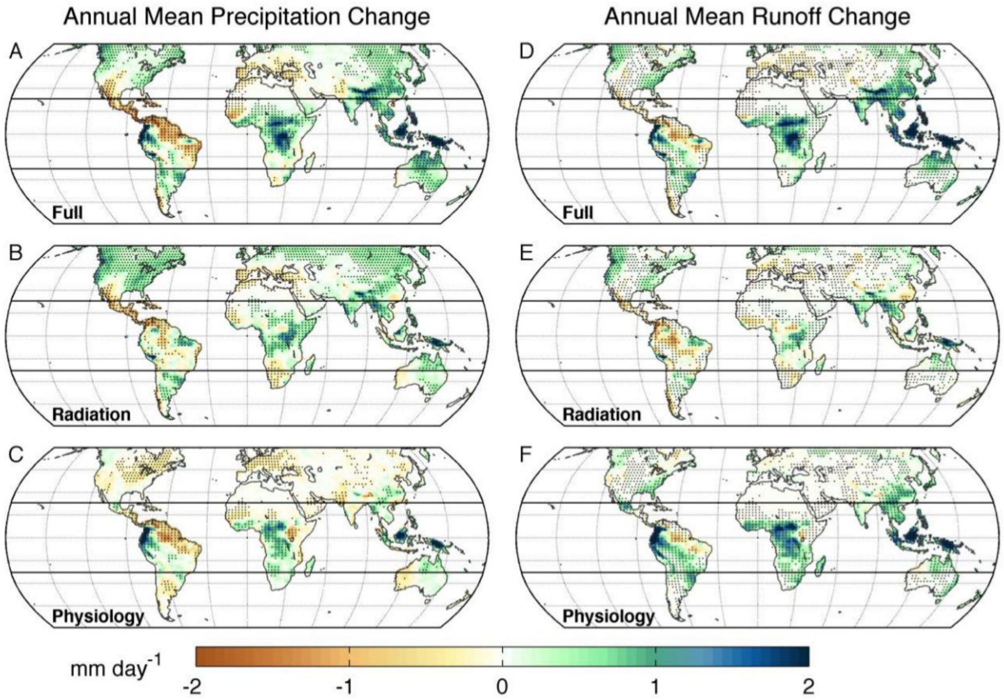
Plant-physiological responses to rising CO_2 increase tropical flood risk



- 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.

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.

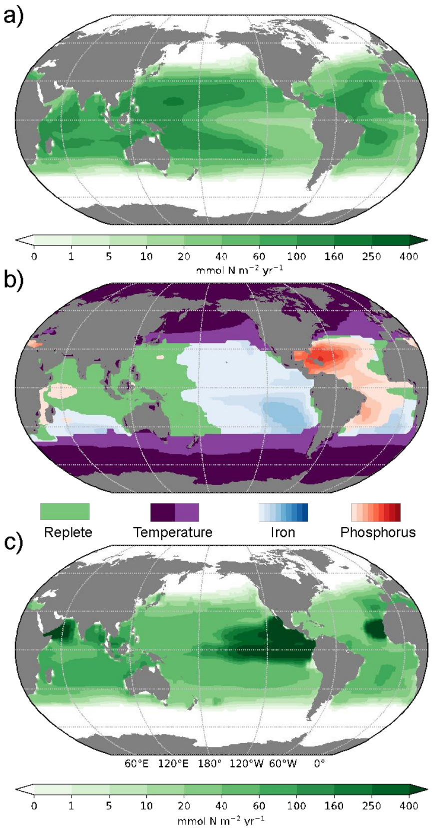

Figure: Prognostic model simulations of diazotrophs and N_2 fixation. Panel C has reduced grazing on the N fixing phytoplankton.

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

E3SM Energy Exascale Earth System Model

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.

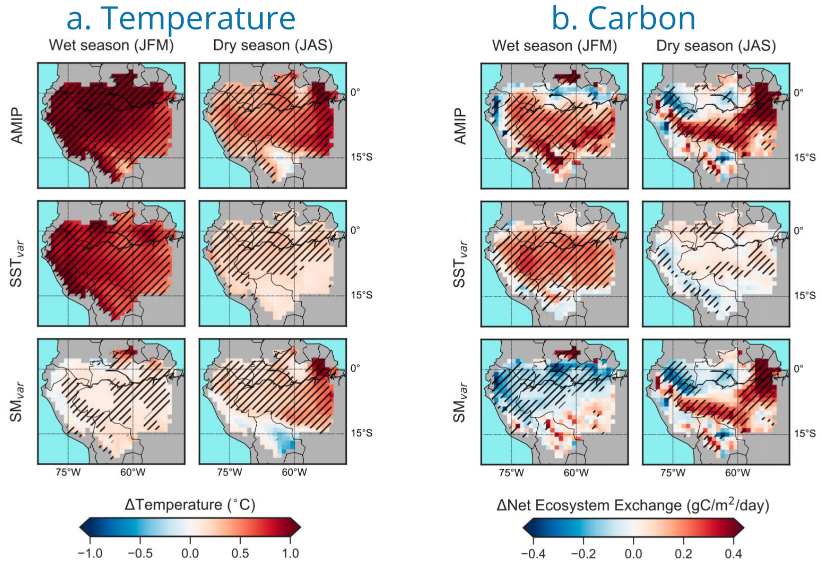

Figure: a. The difference between the mean temperature anomalies of El Niño years and those of La Niña years. Monthly anomalies are averaged across the wet season (JFM, left column) and dry season (JAS, right column). Each experiment (row) is described in the Approach section of the text. b. Same as 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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ILAMB package provides rigorous model benchmarking capabilities

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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.

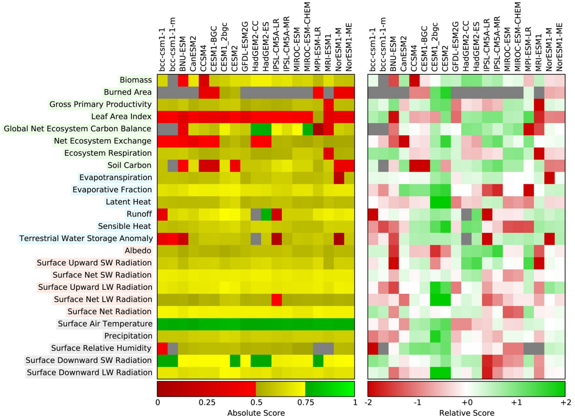

Figure: ILAMB scores land models (columns) across a variety of variables (rows).

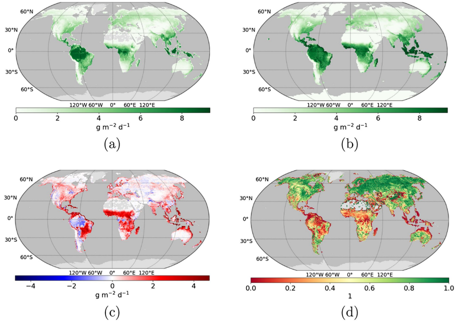

Figure: Example model–data comparison for gross primary production (GPP).

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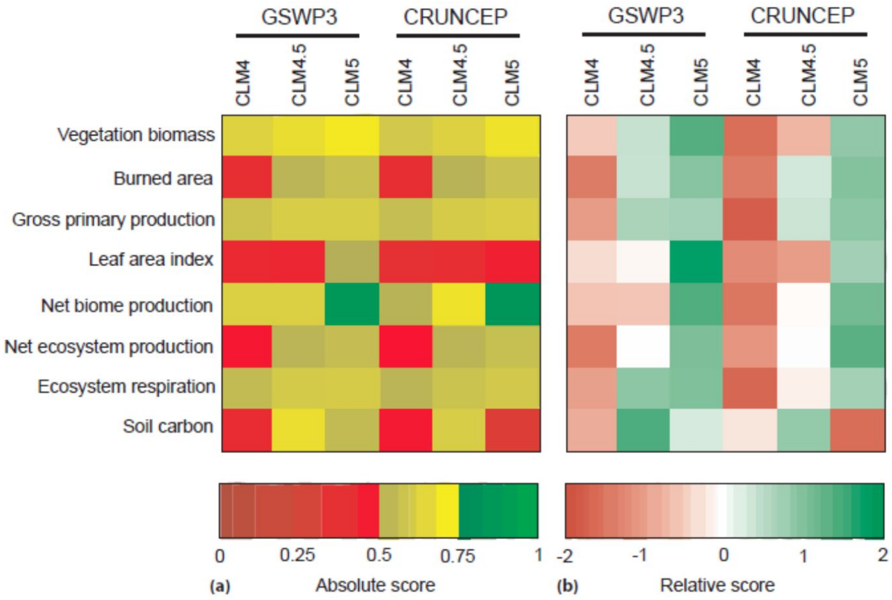
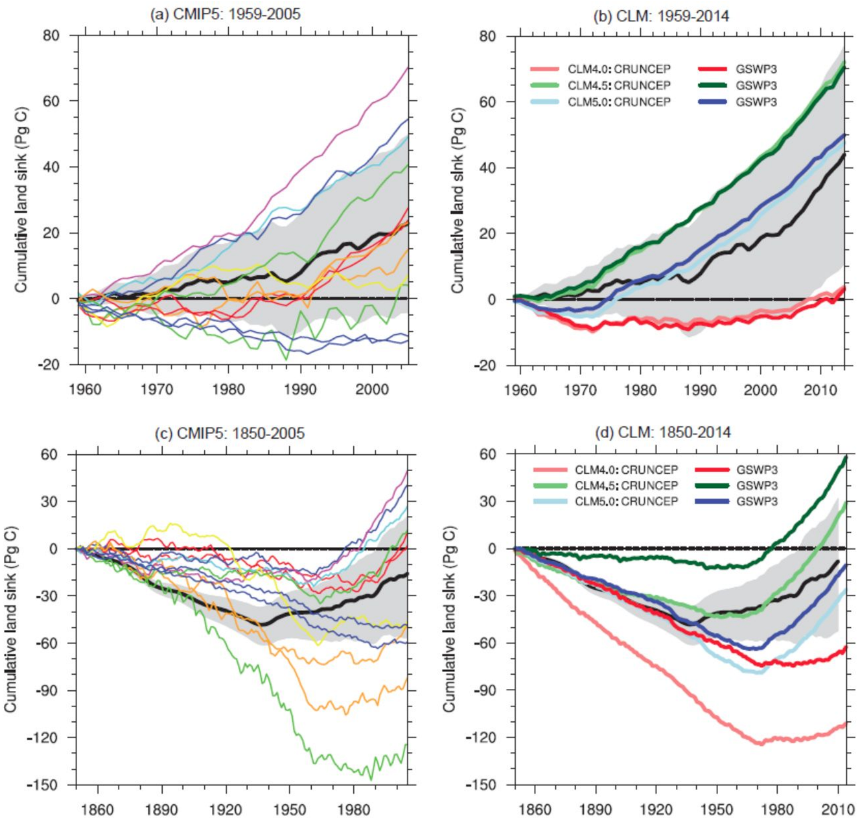
Land Model Performance Depends Strongly on Forcing





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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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)

	bcc-csm1-1	CanESM2	CESM1-BGC	GFDL-ESM2G	IPSL-CM5A-LR	MIROC-ESM	MPI-ESM-LR	NorESM1-ME	UK-HadGEM2-ES	BCC-CSM2-MR	CanESM5	CESM2	GFDL-ESM4	IPSL-CM6A-LR	MIROC-ES2L	MPI-ESM1.2-LR	NorESM2-LM	UKESM1-0-LL	MeanCMIP5	MeanCMIP6
⊟ Ecosystem and Carbon Cycle			-1.06				0.34	-0.76				1.48								
└ ⊞ Biomass	0.20	-0.45	-1.52	-0.40	-1.26	-0.26	-1.07	-1.77	0.92	1.39	0.74	-0.20	-0.54	0.16	0.93	-0.96	-0.01	1.04	1.23	1.82
└ ⊞ Burned Area			-0.87				0.10	-0.83				1.60								
└ ⊞ Leaf Area Index	-0.20	-0.64	-1.30	-2.53	-0.01	0.30	0.01	-1.85	-0.16	0.27	0.08	0.34	-0.70	1.19	0.82	0.46	0.37	0.69	1.04	1.81
└ ⊞ Soil Carbon	0.27	1.26	-1.46	0.07	0.75	0.47	-0.03	-1.14	0.07	0.23	1.35	-0.99	-2.04	-1.55	0.90	-0.75	-0.17	0.24	1.01	1.48
└ ⊞ Gross Primary Productivity	0.59	-1.23	0.01	-1.81	-1.40	0.29	-0.53	-0.24	-1.04	0.77	0.04	0.59	-0.38	1.17	-1.02	-0.37	0.73	0.09	1.51	2.22
└ ⊞ Net Ecosystem Exchange	-0.42	-1.81	-0.21	-0.65	1.10	-0.24	0.80	0.02	-1.03	-1.02	-1.19	0.59	1.69	-0.42	0.63	-0.21	1.08	-1.43	1.28	1.43
└ ⊞ Ecosystem Respiration	0.90	-0.56	-0.86	-0.24	-1.35	0.99	-0.01	-0.94	-1.54	0.81	0.59	0.51	-0.79	0.90	-0.21	-1.24	0.43	-0.94	1.34	2.21
└ ⊞ Carbon Dioxide		-1.54	-0.36	-2.92	-0.74	1.53	-0.00	0.37	0.85		0.42	0.26	0.39	0.59	1.10	-0.87	0.21	0.69	0.09	-0.07
└ ⊞ Global Net Ecosystem Carbon Balance		-1.64	-0.88	-1.13	0.17	-0.31	-0.38	-0.50	0.24		-0.23	1.34	-1.70	0.17	-0.74	1.45	1.56	0.26	0.92	1.40
⊟ Hydrology Cycle	-2.67	-0.64	0.42	-0.16	-0.39	-0.44	-0.50	0.23	0.63	0.13	-0.76	1.55	-1.12	0.55	-0.65	-0.77	1.04	0.89	0.98	1.68
└ ⊞ Evapotranspiration	-0.82	-0.99	-0.27	-1.02	0.64	-1.14	-0.62	-0.60	0.28	0.39	-1.08	1.09	0.65	0.43	-1.40	-1.01	0.82	1.05	1.41	2.20
└ ⊞ Evaporative Fraction	-0.34	0.74	0.74	-0.14	-0.85	0.21	-1.98	0.22	-0.34	0.10	0.11	1.25	-0.88	1.29	-1.65	-1.81	1.11	-0.06	0.98	1.29
└ ⊞ Runoff	-3.66	-0.35	0.47	0.06	-0.67	-0.57	0.12	0.44	1.33	-0.07	-0.23	0.96	-0.17	-0.19	0.02	-0.05	0.47	0.99	-0.03	1.13
└ ⊞ Latent Heat	-0.02	-0.39	-0.38	-0.93	0.24	-0.98	-0.73	-0.71	-0.21	0.66	-1.20	1.60	0.12	0.42	-1.52	-1.24	1.40	0.40	1.49	1.99
└ ⊞ Sensible Heat	-0.85	-0.20	0.80	-0.28	-1.12	-1.23	-1.67	0.45	0.65	-1.04	0.37	1.02	-0.39	1.19	-0.54	-1.63	0.63	0.92	1.48	1.45
└ ⊞ Terrestrial Water Storage Anomaly	-2.79	-0.45	0.47	0.50	-0.38	0.34	0.35	0.43	0.58	0.15	-0.08	0.95	-2.91	0.43	0.37	0.15	0.39	0.51	0.49	0.50
└ ⊞ Permafrost	-0.88	-2.26	0.01	0.13	0.83	0.69	0.56	0.69	-0.56	-0.11	-3.02	0.83	0.74	-0.18	0.49	0.42	0.89	0.43	0.06	0.23

Relative Scale

Worse Value — Better Value

Missing Data or Error

Argonne National Laboratory · Brookhaven National Laboratory · Berkeley Lab · Los Alamos National Laboratory · NCAR National Center for Atmospheric Research · Oak Ridge National Laboratory · UCI · Michigan

Collaborative and Outreach Activities

Soil Carbon Dynamics Working Group

- 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 2018

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

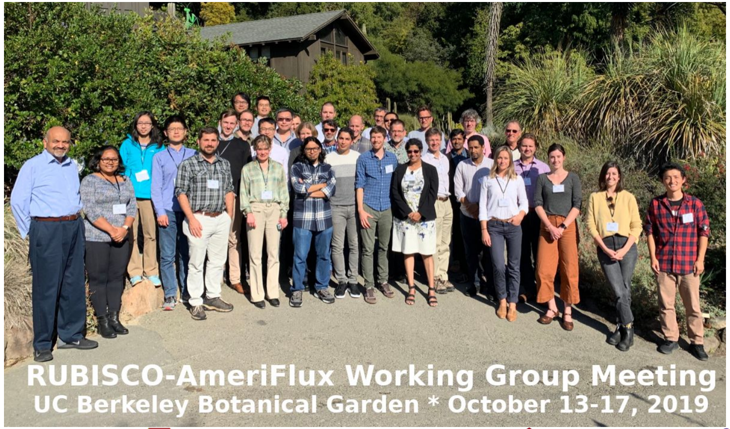
Model–Data Integration Theme

- 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, see *2018 Fall Meeting Report* (June 26, 2019)

RUBISCO-AmeriFlux Working Group

- Formed after community recommendation from the 2016 International Land Model Benchmarking (ILAMB) Workshop Report
- Objective is to use AmeriFlux data to improve process understanding and to develop, parameterize, and test models
- Multiple conference calls led up to a meeting at the UC Berkeley Botanical Garden (outside LBNL) on October 15–17, 2019



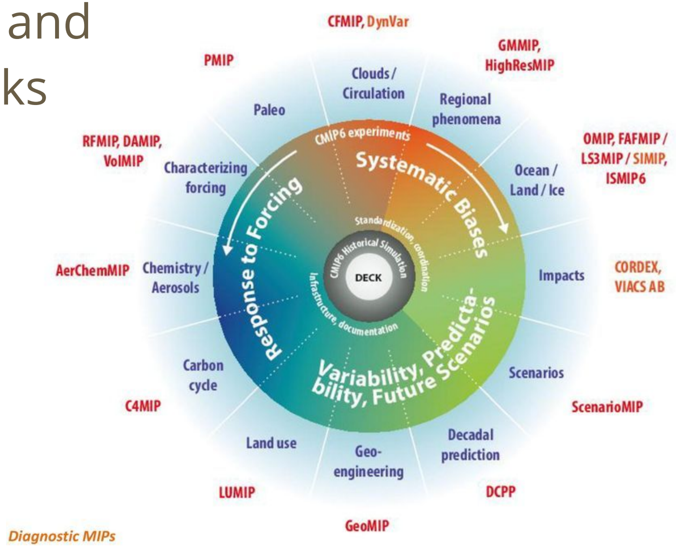
Four key areas of research emerged from the Working Group Meeting:

- **Ecosystem trend spotting** - employing long ecosystem carbon and water flux records to detect trends in ecosystem metabolism and to disentangle responses of ecosystems to elevated CO_2, climate change, and human disturbances
- **Ecosystem responses to extreme events** - use long-running AmeriFlux measurements, which include ecosystem responses to extreme weather conditions, to evaluate models
- **Untangling contributions to carbon exchange** - use complementary measurements of respiration fluxes and satellite-derived vegetation indices to improve partitioning methods for eddy covariance estimates of GPP and R_{eco}
- **Scaling up from sites to ecosystems** - combine bottom-up and top-down approaches for scaling fluxes across spatial scales

For more information, see Measuring, Monitoring, and Modeling Ecosystem Cycling in *Eos Trans. AGU* (August 5, 2020)

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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