INS 31: Advancing the Predictive Ability of the Global Carbon Cycle in Earth System Models

Systematic model–data comparison for advancing global carbon cycle models

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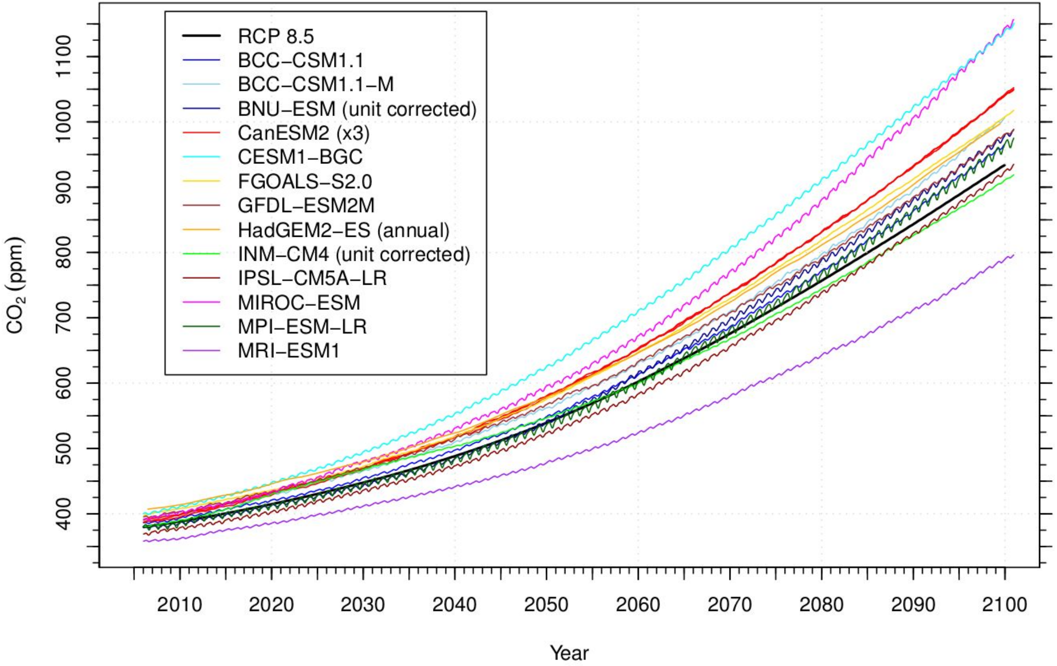
Predictive ability of carbon cycle models is limited by large uncertainties in projections of climate and ecosystem responses

ESM RCP 8.5 Atmospheric CO_2 Mole Fraction



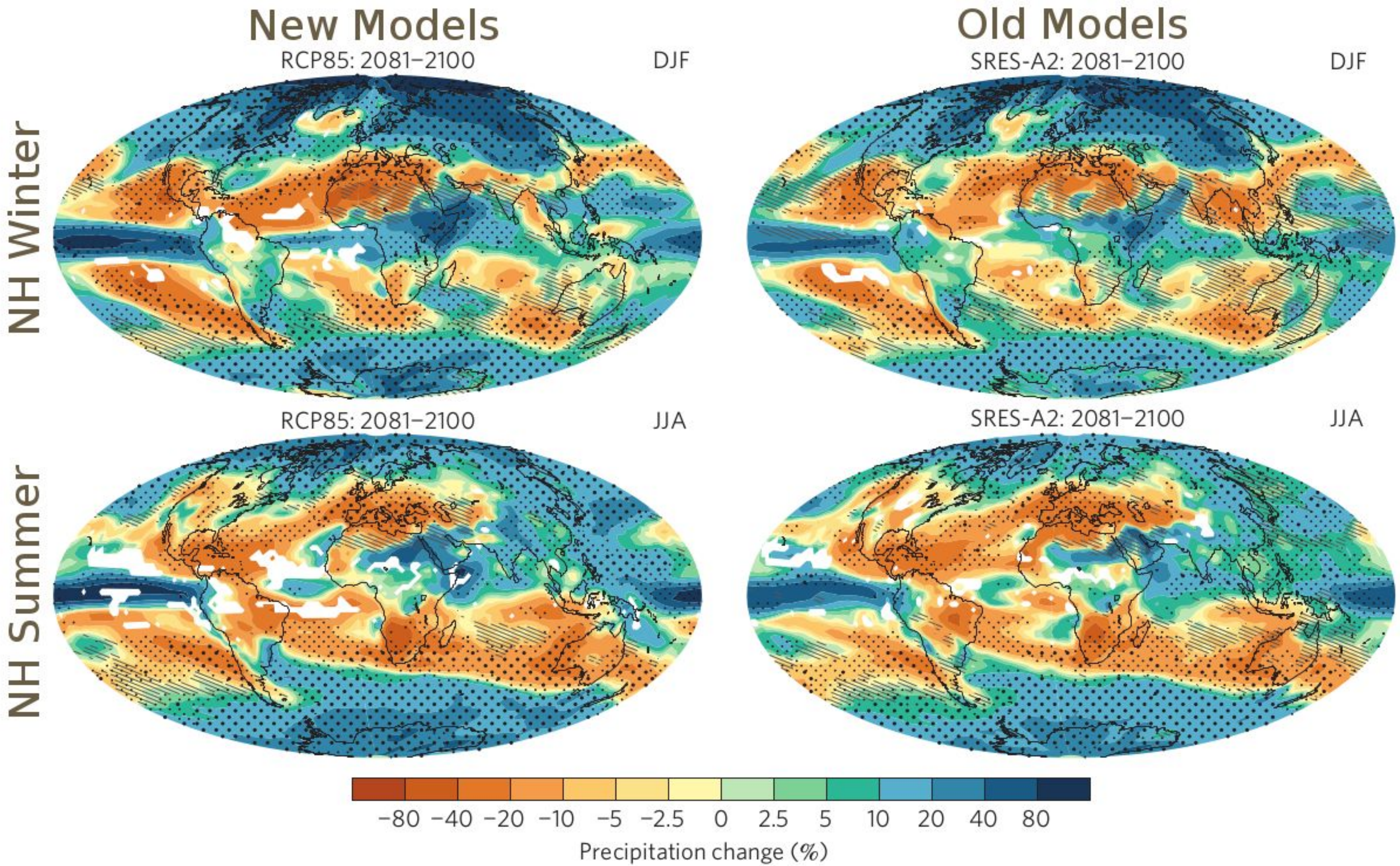
(Hoffman et al., 2014)

Model uncertainty is one of the biggest challenges we face in Earth system science, yet comparatively little effort is devoted to fixing it (*Carslaw et al.*, 2018)

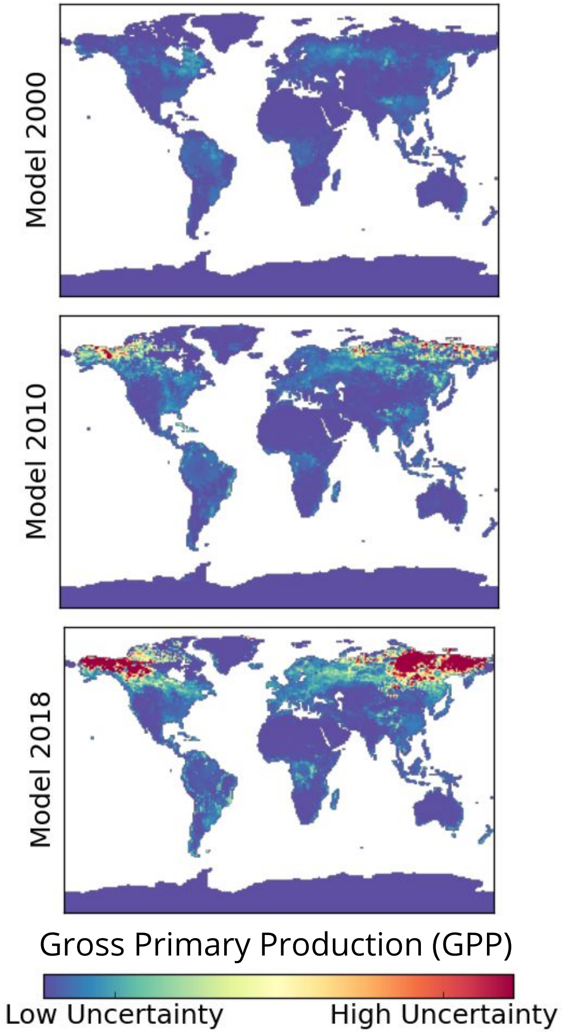
Solution to the Model Uncertainty Problem?

- Add model complexity?
- May introduce uncertain parameters.
- When do we stop digging?

Patterns of precipitation changes across two generations of models



(Adapted from *Knutti and Sedláček*, 2013)



In 3 generations of a land model,

- Annual gross primary production (GPP) progressively improved
- Yet the uncertainty increased in some regions

The Solution? Careful Examination!

Paths to reducing model discordance:

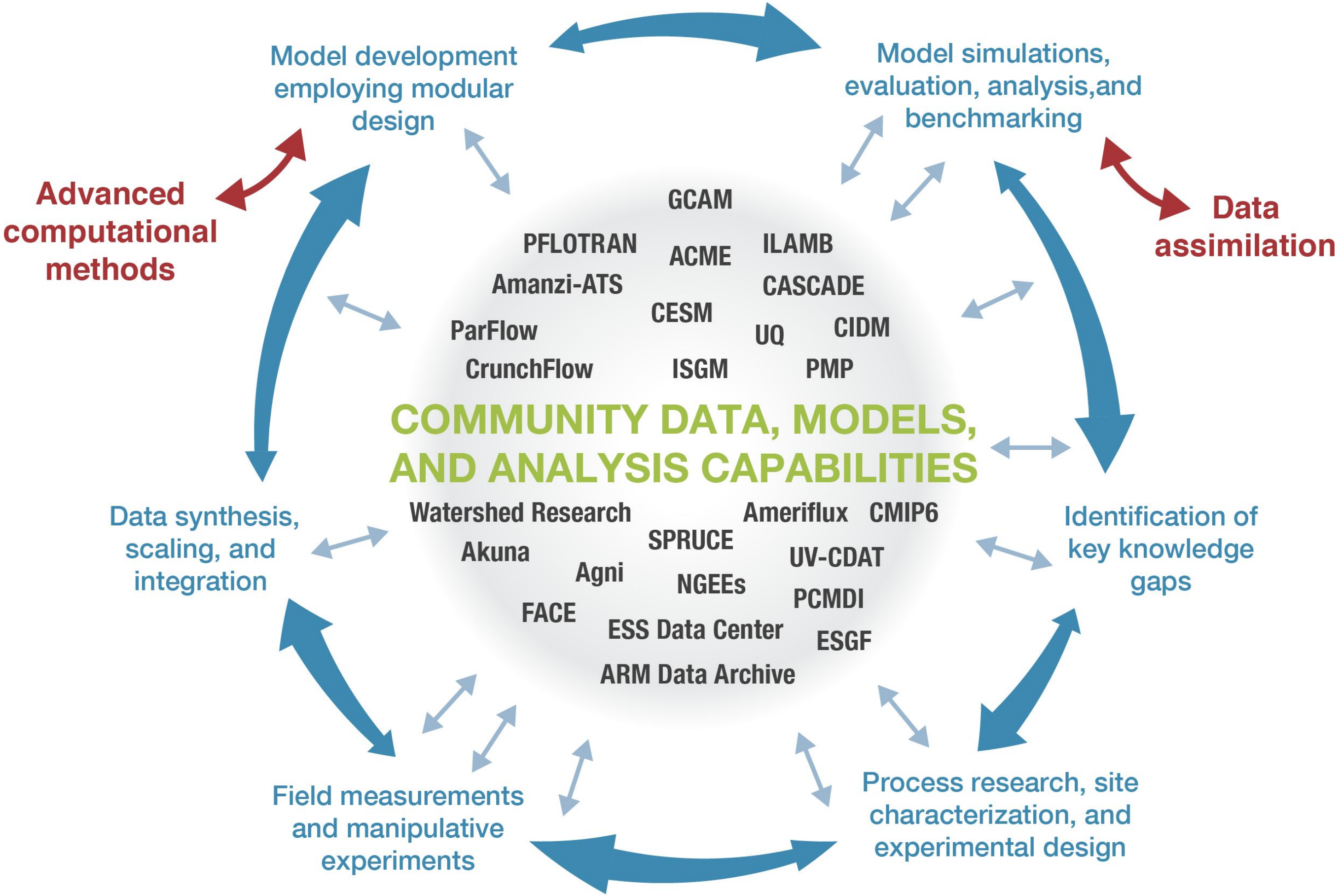
1. Confront models with many independent observations
2. Routinely generate ensemble simulations

Why Have These Challenges Not Been Addressed?

- Lack of computational resources and poor software infrastructure
- Hodge-podge of existing diagnostics (good enough?)
- Lots of data needed to characterize ecosystem responses
- Focus is on adding model complexity (elaboration)

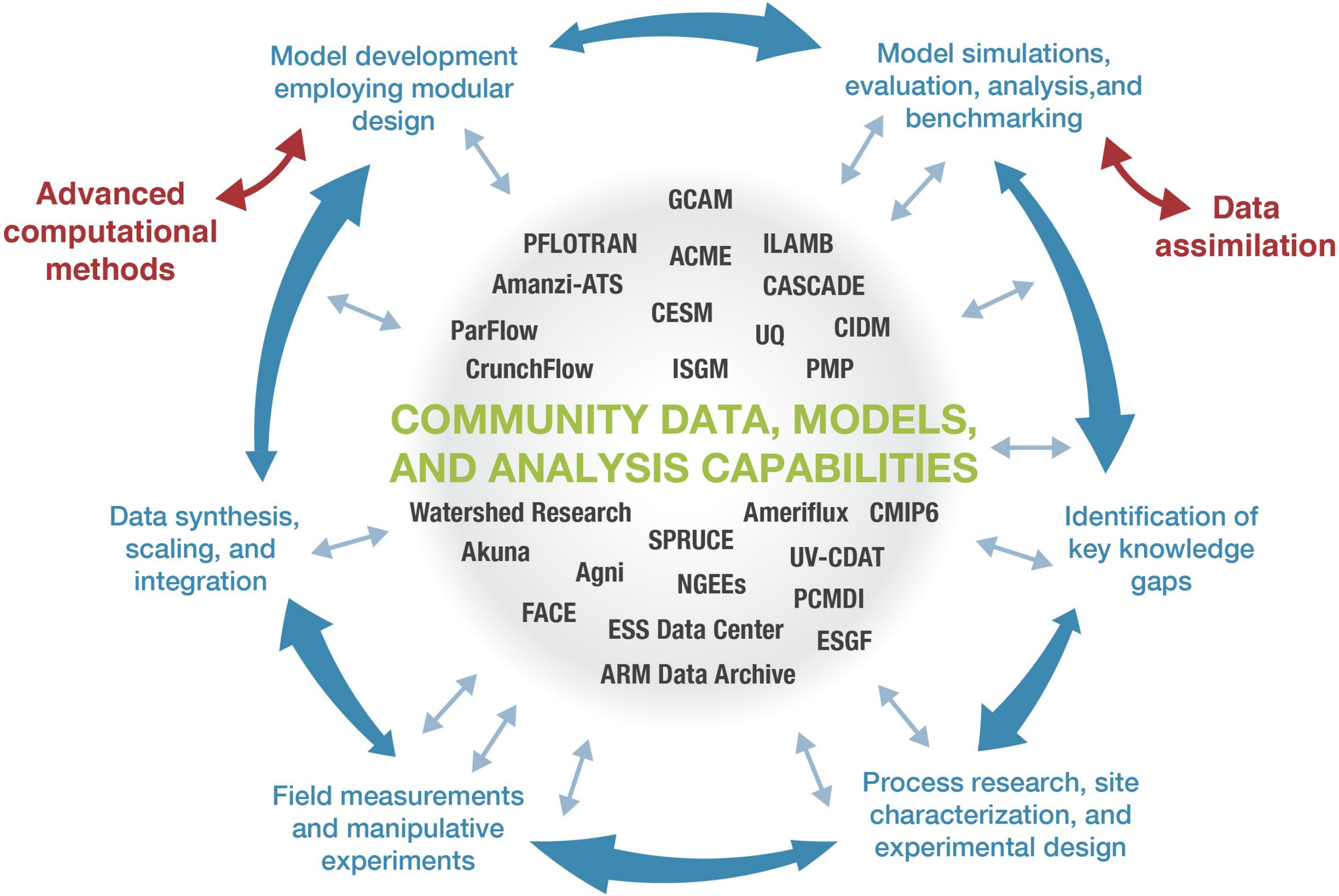
DOE-BER's Model-Data-Experiment Enterprise

The aim of DOE's Biological and Environmental Research (BER) is ***to develop a predictive understanding of complex biological and environmental systems***



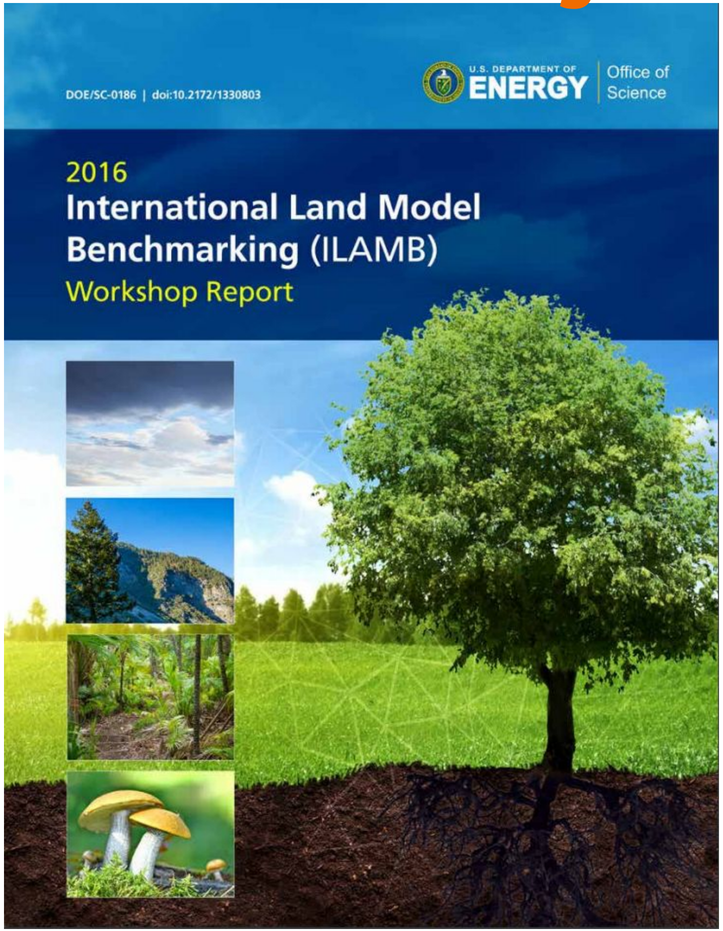
DOE-BER's Model-Data-Experiment Enterprise

- Process research and field experiments are time-consuming and expensive
- Synthesis, development, simulation, and analysis are slow and often neglect uncertainty



Path 1: International Land Model Benchmarking

- An international community effort to design metrics and build software infrastructure for benchmarking
- Conduct systematic assessment of land model results compared with observations
- Score model performance across a wide range of independent benchmark data sets



ILAMB Model Benchmarking Package

- "Portrait plots" of absolute and relative model scores
- Aggregated scores from multiple data sets and metrics for each variable
- Hierarchical user interface for analysis results

ILAMB Package Results Table

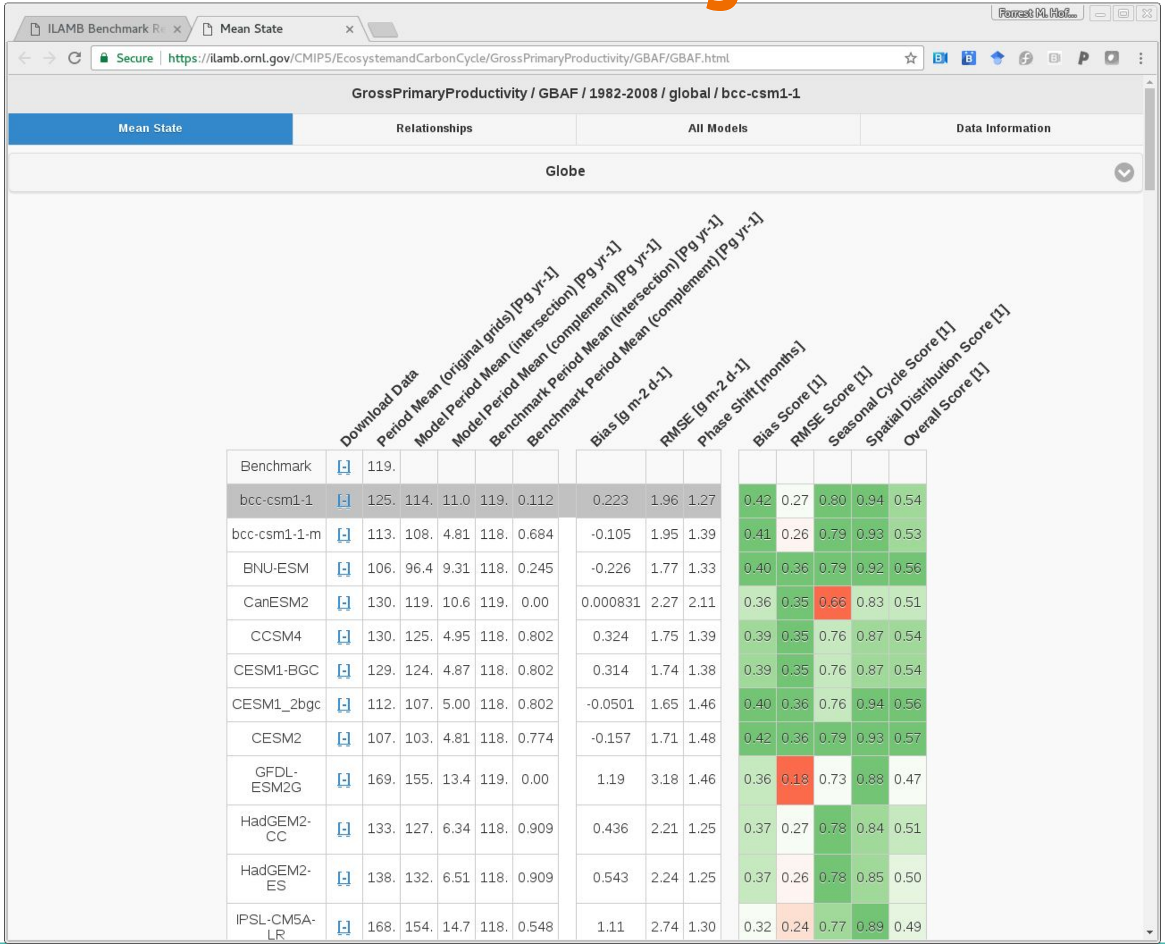
ILAMB Benchmark Results

Mean State | Relationship | Results Table

Biomass	0.63	~	0.47	0.68	0.27	0.59	0.62	0.66	0.66	0.71	0.71	0.67	0.68	0.62
Burned Area	~	~	~	~	0.38	0.38	0.51	0.55	~	~	~	~	~	~
Gross Primary Productivity	0.57	0.56	0.59	0.54	0.57	0.57	0.60	0.60	0.51	0.54	0.54	0.53	0.53	0.58
Fluxnet (37.5%)	0.63	0.61	0.64	0.58	0.60	0.61	0.66	0.65	0.59	0.61	0.60	0.58	0.60	0.64
GBAF (62.5%)	0.54	0.53	0.56	0.51	0.54	0.54	0.56	0.57	0.47	0.51	0.50	0.49	0.49	0.55
Leaf Area Index	0.47	0.48	0.33	0.46	0.40	0.40	0.39	0.49	0.37	0.48	0.48	0.49	0.49	0.47
Global Net Ecosystem Carbon Balance	~	~	0.39	0.62	0.60	0.57	0.71	0.62	0.60	0.78	0.77	0.72	0.66	0.74
Net Ecosystem Exchange	0.50	0.49	0.46	0.39	0.49	0.49	0.53	0.56	0.51	0.48	0.48	0.54	0.54	0.51
Ecosystem Respiration	0.60	0.60	0.61	0.56	0.53	0.53	0.58	0.59	0.57	0.52	0.52	0.53	0.54	0.61
Soil Carbon	0.58	~	0.50	0.66	0.24	0.24	0.67	0.43	0.59	0.59	0.61	0.67	0.70	0.63
Ecosystem and Carbon Cycle Summary	~	~	~	~	0.44	0.48	0.59	0.57	~	~	~	~	~	~
Evapotranspiration	0.58	0.58	0.57	0.56	0.57	0.57	0.63	0.65	0.54	0.59	0.58	0.61	0.61	0.56
Evaporative Fraction	0.67	0.66	0.68	0.71	0.70	0.70	0.72	0.72	0.68	0.68	0.67	0.64	0.64	0.68
Latent Heat	0.57	0.56	0.56	0.56	0.56	0.56	0.63	0.65	0.54	0.56	0.56	0.58	0.58	0.55
Runoff	0.37	0.64	0.66	0.63	0.69	0.70	0.74	0.73	0.67	~	0.78	0.26	0.62	0.62
Sensible Heat	0.58	0.56	0.57	0.59	0.62	0.62	0.64	0.65	0.59	0.63	0.63	0.60	0.59	0.56
Terrestrial Water Storage Anomaly	0.38	0.46	0.22	0.55	0.60	0.60	0.59	0.59	0.57	~	0.60	0.07	0.55	0.59
Hydrology Cycle Summary	0.52	0.58	0.54	0.60	0.62	0.63	0.66	0.67	0.60	~	0.64	0.44	0.60	0.59

- Results Table shows scores for each model (columns) by variable (rows)
- Each variable is a “pull-down” for multiple data sets

ILAMB Package Metrics and Scores Table

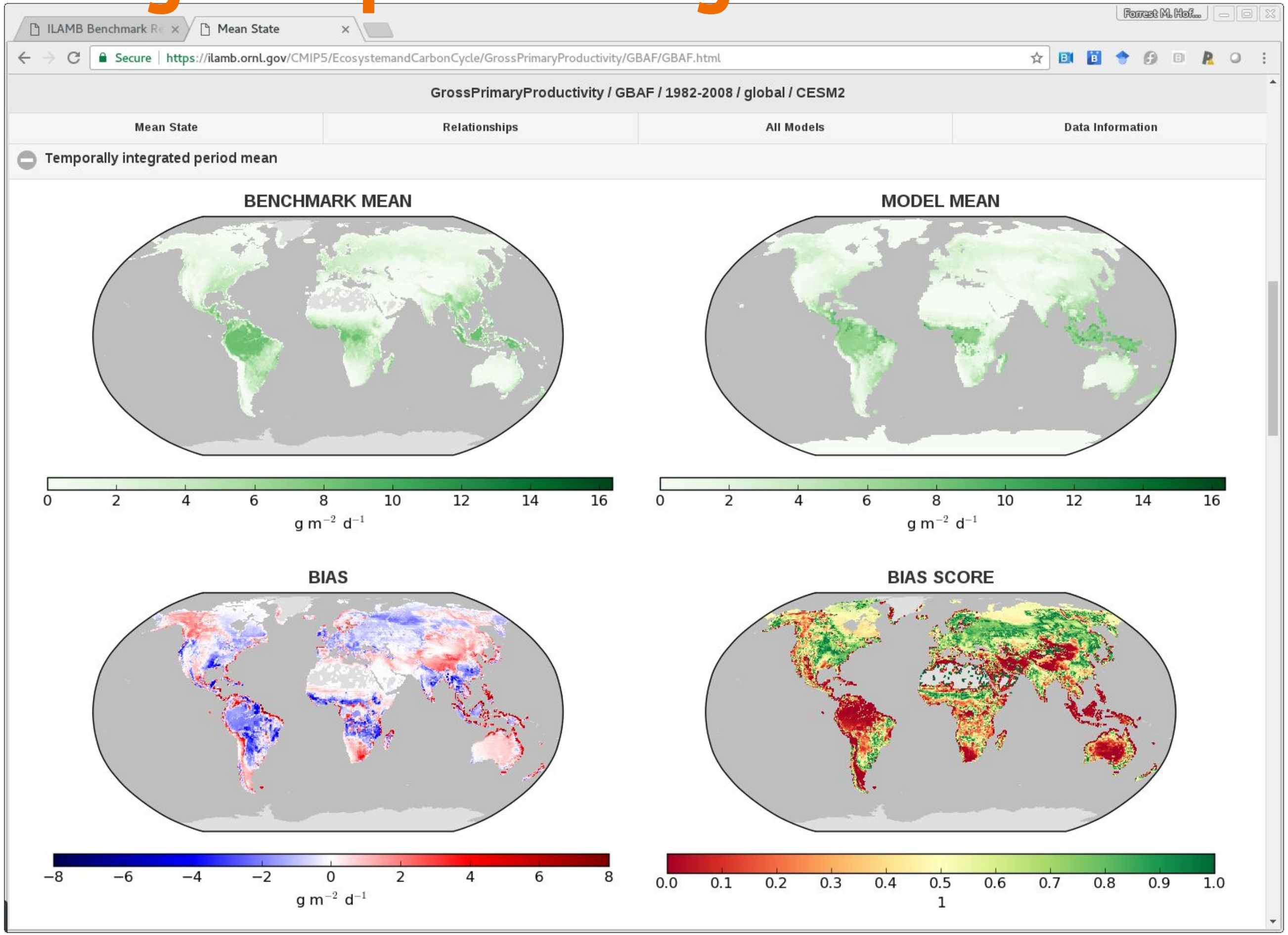


	Download Data	Period Mean (original grids) [Pg yr-1]	Model Period Mean (intersection) [Pg yr-1]	Model Period Mean (complement) [Pg yr-1]	Benchmark Period Mean (intersection) [Pg yr-1]	Benchmark Period Mean (complement) [Pg yr-1]	Bias [g m-2 d-1]	RMSE [g m-2 d-1]	Phase Shift [months]	Bias Score [1]	RMSE Score [1]	Seasonal Cycle Score [1]	Spatial Distribution Score [1]	Overall Score [1]
Benchmark	[-]	119.												
bcc-csm1-1	[-]	125.	114.	11.0	119.	0.112	0.223	1.96	1.27	0.42	0.27	0.80	0.94	0.54
bcc-csm1-1-m	[-]	113.	108.	4.81	118.	0.684	-0.105	1.95	1.39	0.41	0.26	0.79	0.93	0.53
BNU-ESM	[-]	106.	96.4	9.31	118.	0.245	-0.226	1.77	1.33	0.40	0.36	0.79	0.92	0.56
CanESM2	[-]	130.	119.	10.6	119.	0.00	0.000831	2.27	2.11	0.36	0.35	0.66	0.83	0.51
CCSM4	[-]	130.	125.	4.95	118.	0.802	0.324	1.75	1.39	0.39	0.35	0.76	0.87	0.54
CESM1-BGC	[-]	129.	124.	4.87	118.	0.802	0.314	1.74	1.38	0.39	0.35	0.76	0.87	0.54
CESM1_2bgc	[-]	112.	107.	5.00	118.	0.802	-0.0501	1.65	1.46	0.40	0.36	0.76	0.94	0.56
CESM2	[-]	107.	103.	4.81	118.	0.774	-0.157	1.71	1.48	0.42	0.36	0.79	0.93	0.57
GFDL-ESM2G	[-]	169.	155.	13.4	119.	0.00	1.19	3.18	1.46	0.36	0.18	0.73	0.88	0.47
HadGEM2-CC	[-]	133.	127.	6.34	118.	0.909	0.436	2.21	1.25	0.37	0.27	0.78	0.84	0.51
HadGEM2-ES	[-]	138.	132.	6.51	118.	0.909	0.543	2.24	1.25	0.37	0.26	0.78	0.85	0.50
IPSL-CM5A-LR	[-]	168.	154.	14.7	118.	0.548	1.11	2.74	1.30	0.32	0.24	0.77	0.89	0.49

Statistics and graphical diagnostics are produced globally and for pre-defined regions

ILAMB Package Graphical Diagnostics

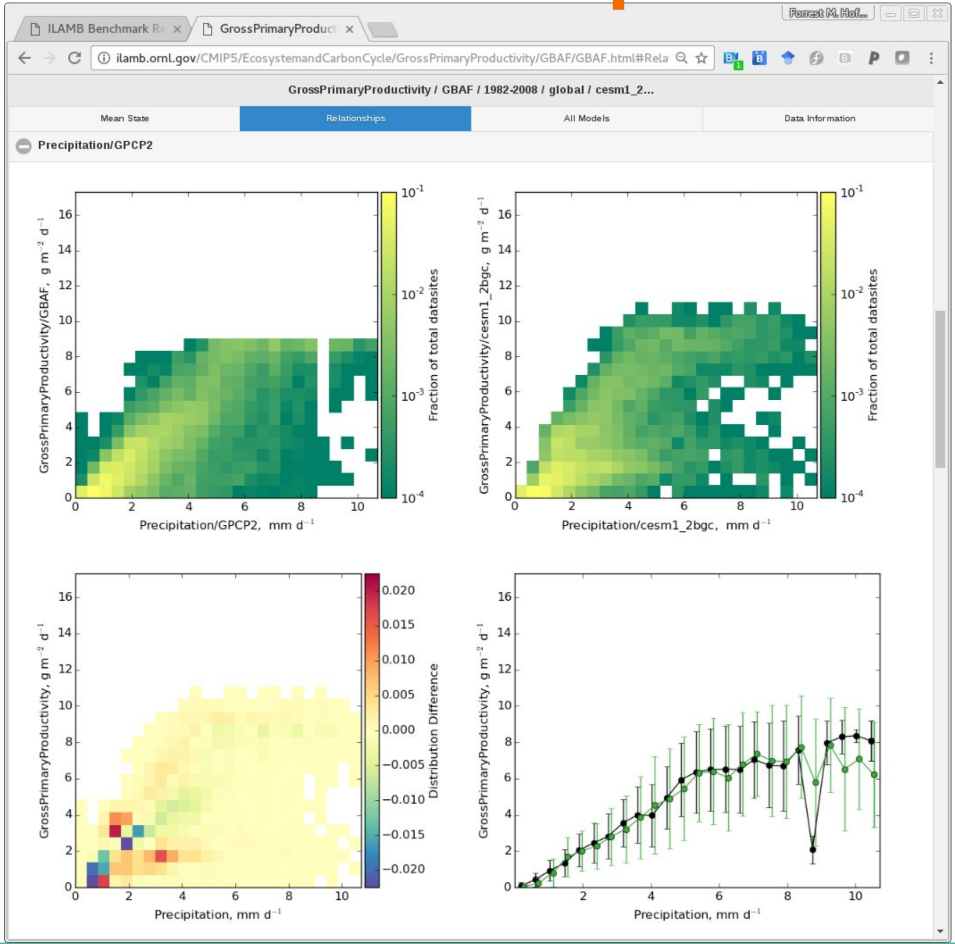
Models are scored based on variable bias, RMSE, seasonal cycle, interannual variability, and spatial distribution



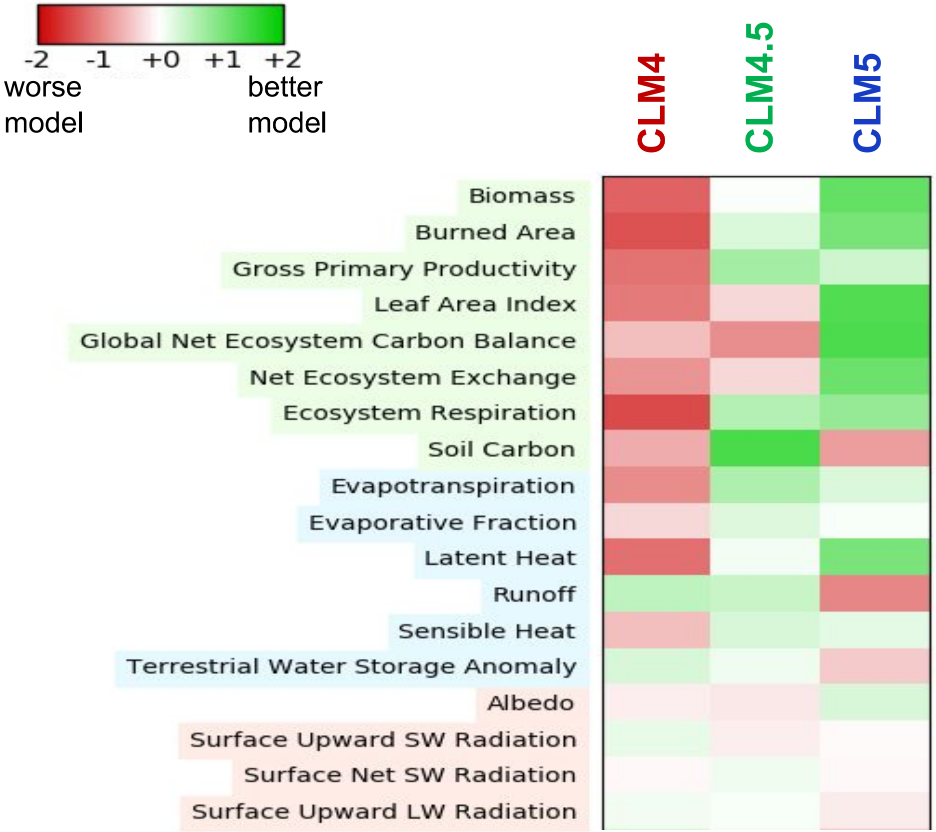
ILAMB Package Functional Relationships

A way to assess and understand model responses to forcing!

- Differences in distribution of points suggests regimes for which model errors are most significant
- Histogram-style line plots indicate if model exhibits overall relationships that emerge from observations



ILAMB Assessing Several Generations of CLM



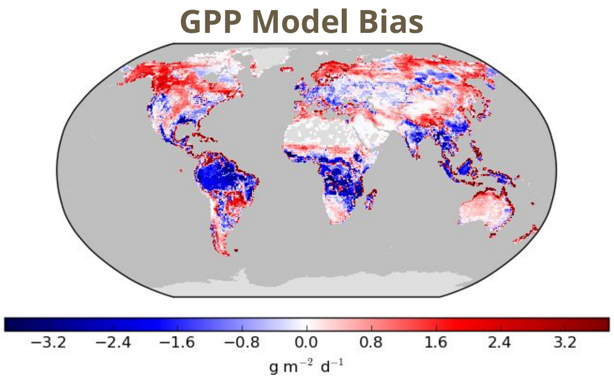
- Improvements in mechanistic treatment of hydrology, ecology, and land use
- Simulation improved even with enhanced complexity

(*Lawrence et al.*, in prep)

Path 2: Land Model Testbed (LMT)

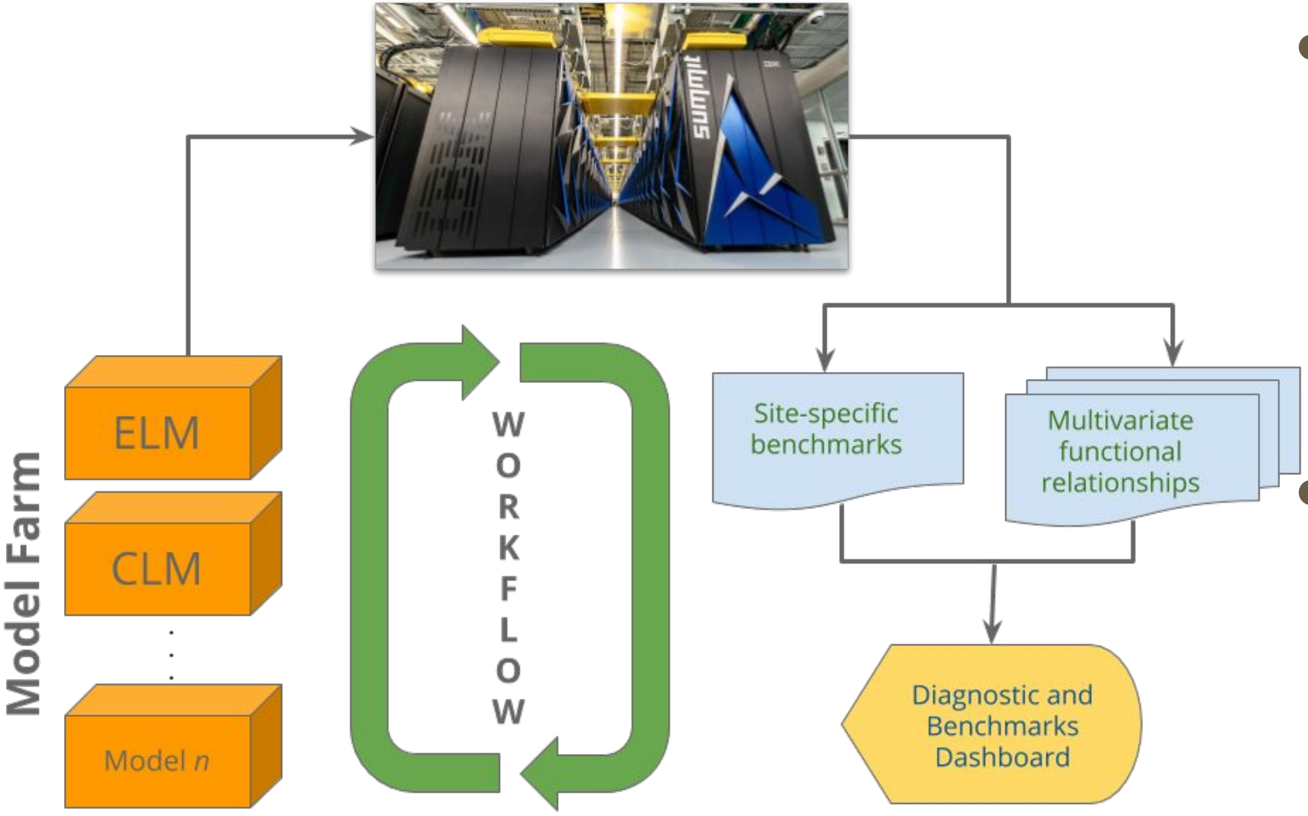
Software infrastructure to:

- Produce large ensembles
- Explore structural uncertainty
- Lower barrier for process specialists to test hypotheses in models
- Support rapid development of complex multiscale models
- PEcAn package offers many capabilities for point/site simulations today



PEcAn

Global LMT for High Performance Computing



- Need a second generation system for global simulations on supercomputers
- And modular interfaces for testing process modules within a single model

In Summary...

- Carbon cycle predictability is limited by process-level uncertainty and resulting multi-model discordance.
- Adding complexity may or may not reduce uncertainty or improve model fidelity.
- Progress in reducing multi-model differences can come from
    - Systematic model assessment and benchmarking
    - Land model testbeds for uncertainty characterization