



U.S. DEPARTMENT
of ENERGY

Systematic Evaluation of Earth System Models

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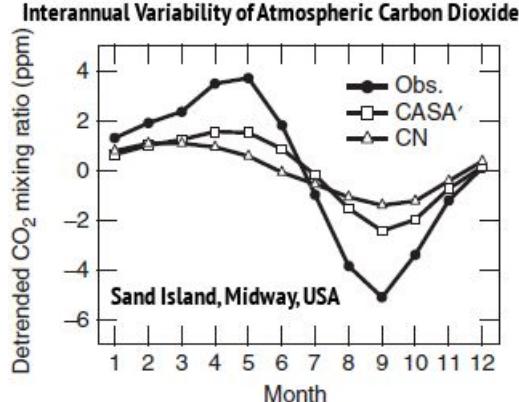
NGEE Arctic MODEX Workshop – Santa Fe, New Mexico
January 15, 2026



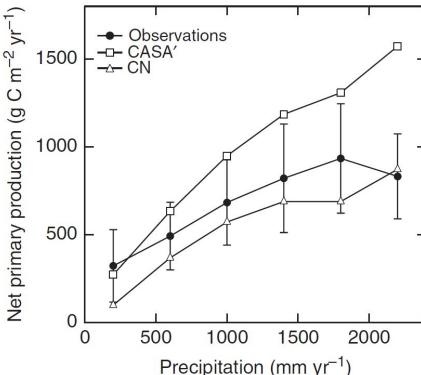


What is a Benchmark?

- A **benchmark** is a quantitative test of model function achieved through comparison of model results with observational data
- Acceptable performance on a benchmark **is a necessary but not sufficient condition** for a fully functioning model
- **Functional relationship 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 at multiple scales



Models often fail to capture the amplitude of the seasonal cycle of atmospheric composition



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



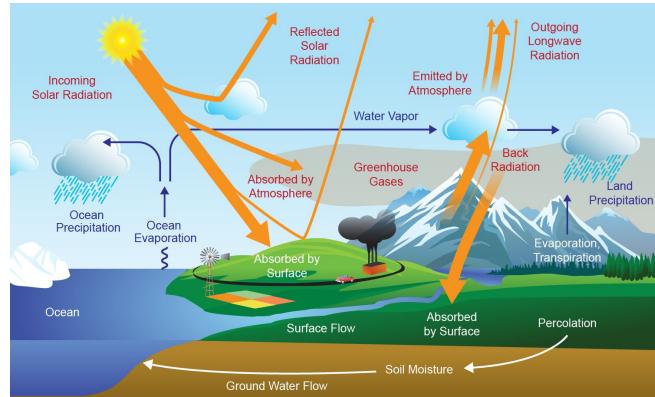
(Randerson et al., 2009)



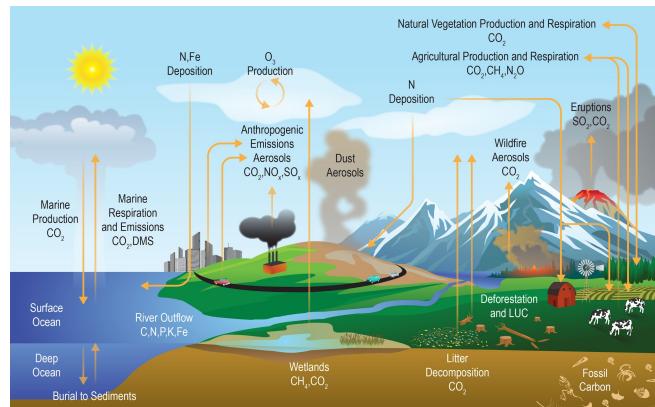
What is ILAMB?

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 Earth system modeling communities** in the design of new model tests and new measurement programs
- **Support the design and development of open source benchmarking tools**



Energy and Water Cycles



Biogeochemical Cycles



ILAMB Produces Diagnostics and Scores Models

- ILAMB generates a top-level **portrait plot** of models scores
- For every variable and dataset, ILAMB can automatically produce
 - **Tables** containing individual metrics and metric scores (when relevant to the data), including
 - Benchmark and model **period mean**
 - **Bias** and **bias score** (S_{bias})
 - **Root-mean-square error (RMSE)** and **RMSE score** (S_{rmse})
 - **Phase shift** and **seasonal cycle score** (S_{phase})
 - **Interannual coefficient of variation** and **IAV score** (S_{iav})
 - **Spatial distribution score** (S_{dist})
 - **Overall score** (S_{overall})
 - **Graphical diagnostics**
 - Spatial contour maps
 - Time series line plots
 - Spatial Taylor diagrams (Taylor, 2001)
- Similar **tables** and **graphical diagnostics** for functional relationships



ILAMBv2.7 Package Current Variables

- **Biogeochemistry:** Biomass (Contiguous US, Pan Tropical Forest), Burned area (GFED3), CO₂ (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 & IOMB CMIP5 vs 6 Evaluation

Evaluation of CMIP5 vs CMIP6 with ILAMB and IOMB

- (a) ILAMB and (b) IOMB have been used to evaluate how land and ocean model performance has changed from CMIP5 to CMIP6
- Model fidelity is assessed through comparison of historical simulations with a wide variety of contemporary observational datasets
- The UN's Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6) from Working Group 1 (WG1) Chapter 5 contains the full ILAMB/IOMB evaluation as Figure 5.22

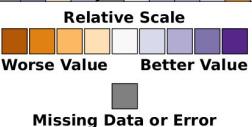
(a) Land Benchmarking Results

Land Ecosystem & Carbon Cycle

	bcc-csm1-1	CanESM2	CESM1-BGC	GFDL-ESM2G	IPSL-CM5A-LR	IPSL-CM5A-MR	MIROC-ESM	MIROC-ESM-LR	NorESM1-ME	HadGEM2-ES	BCC-CM2-MR	CanESM5	CESM2	GFDL-ESM4	IPSL-CM6A-LR	IPSL-CM6A-LR	MRI-ES2L	MRI-ES2L	MPI-ESM1-2-LR	MPI-ESM1-2-LR	NorESM2-LM	NorESM2-LM	UKESM1-0-LL	UKESM1-0-LL	Mean CMIP5	Mean CMIP6	
Biomass	-0.72	-0.93	1.55	-1.51	-0.13	0.60	-0.43	1.31	0.19	-0.43	0.66	0.48	-1.09	0.22	0.60	-0.07	1.00	0.49	1.63	2.30							
Burned Area	0.20	-0.45	1.92	-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							
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	1.41							
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	2.73							
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 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	0.56	1.26	0.92	1.40								
Land Hydrology Cycle																											
Evapotranspiration	-0.82	-0.99	0.27	-0.02	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	-0.14	-0.85	0.21	-0.98	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								
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	3.07	0.83	0.74	-0.18	0.49	0.42	0.89	0.43	0.06	0.23							

(b) Ocean Benchmarking Results

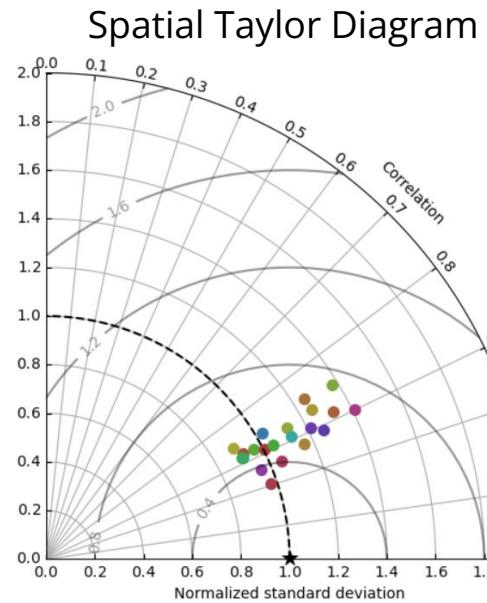
	Ocean Ecosystems	Chlorophyll	Oxygen, surface	Ocean Nutrients	Nitrate, surface	Phosphate, surface	Silicate, surface	Ocean Carbon	TAlk, surface	Salinity, 700m	Ocean Relationships	Oxygen, surface/WOA2018	Nitrate, surface/WOA2018												
	-0.20	-0.20	0.04	0.22	-0.37	0.83	-0.37	0.26	0.91	-0.67	1.93	0.27	0.30	0.67											
Chlorophyll	-1.50	0.10	0.44	1.02	0.49	0.56	-0.67	0.88	-0.21	0.10	1.02	-0.41	2.19	0.18	0.13	0.04									
Oxygen, surface	0.73	-0.13	-1.98	-0.53	-1.53	-0.29	0.73	0.34	-0.09	-0.41	0.35	-0.30	0.40	0.49	0.64	1.57									
Ocean Nutrients	0.84	-0.10	0.91	-0.80	-1.25		-0.02	1.00	1.88	-0.90	-1.14	-0.17	-0.16	1.60											
Nitrate, surface	0.21	1.60	0.67	1.22	-0.18	1.70	0.82	1.21	-0.90	0.29	1.21	1.02	0.39	1.78	-0.56	0.47	0.18								
Phosphate, surface	0.69	0.04	0.04	-0.45	0.43		0.39	-0.14	0.17	-0.41	0.98	0.00	0.02	0.88	1.63										
Silicate, surface	0.44	0.71	0.24	-0.81	-0.20	-2.16	0.50	1.24	1.60	-1.21	-0.19	0.18	-0.29	1.37											
Ocean Carbon	-0.27	1.01	0.12	0.19	0.32	-2.31	-0.22	0.06	-0.36	0.85	-0.42	0.29	-0.46	1.27	0.06	1.27	0.54								
TAlk, surface	0.44	-0.35	-1.06	-0.54	0.70	0.46	-0.80	0.32	0.36	0.25	-1.16	-0.47	0.54	0.33	-0.39	-0.87	-0.54								
Salinity, 700m	1.86	-0.36	-0.29	1.50	0.43	0.68	-0.02	0.72	1.20	0.17	-1.80	0.02	-1.12	0.39	1.25										
Ocean Relationships	0.27	0.23	-0.63	-0.26	-0.12	-0.38	0.29	-0.21	0.19	0.18	0.14	-0.07	0.03	-0.23	0.53										
Oxygen, surface/WOA2018	-2.41	1.38	-0.18	0.06	1.41	0.16	0.78	0.09	0.79	1.07	0.26	1.35	0.20	-0.74	0.52	1.04									
Nitrate, surface/WOA2018																									



Gross Primary Productivity

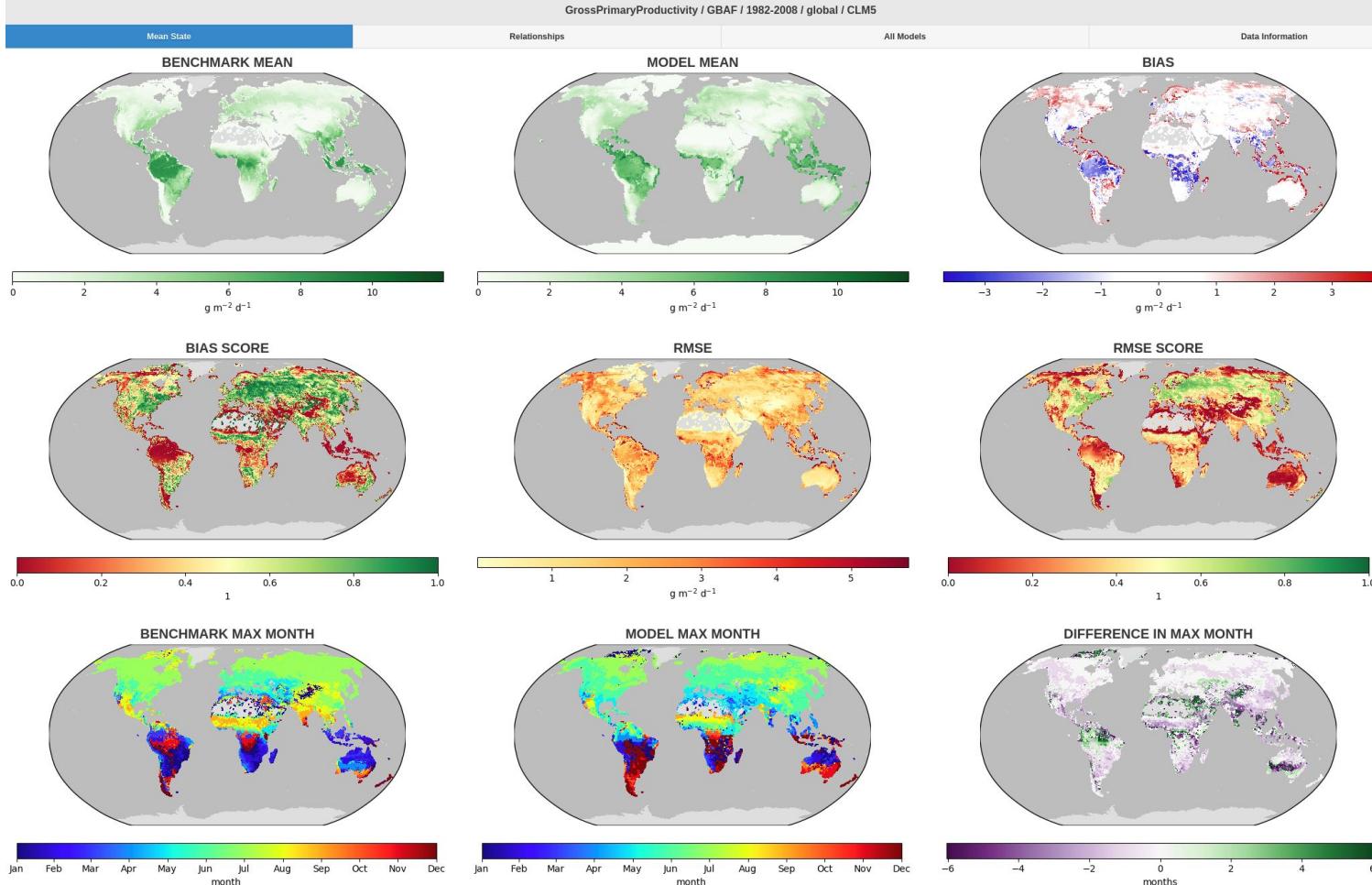
- Multimodel GPP is compared with global seasonal GBAF estimates
- We can see improvements across generations of models (e.g., CESM1 vs. CESM2, IPSL-CM5A vs. 6A)
- The mean CMIP6 and CMIP5 models perform best

Benchmark	Download Data	Period Mean (original grids) [Pg yr-1]	Model Period Mean (Intersection) [Pg yr-1]	Benchmark Period Mean (Intersection) [Pg yr-1]	Model Period Mean (complement) [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]
bcc-csm1-1	[14]	114.												
BCC-CSM2-MR	[14]	123.	112.	114.	8.79	0.0945	0.238	1.51	1.01	0.484	0.435	0.830	0.955	0.628
CanESM2	[14]	129.	117.	114.	9.54		-0.0233	1.52	1.11	0.479	0.447	0.817	0.941	0.626
CanESM5	[14]	141.	128.	114.	10.1		0.0601	2.31	2.00	0.388	0.437	0.850	0.838	0.549
CESM1-BGC	[14]	129.	123.	113.	5.55	0.660	0.730	1.87	1.60	0.449	0.418	0.710	0.948	0.589
CESM2	[14]	110.	104.	113.	5.57	0.642	0.379	1.66	1.20	0.426	0.468	0.765	0.889	0.603
GFDL-ESM2G	[14]	167.	152.	114.	12.4		-0.0542	1.62	1.32	0.458	0.466	0.774	0.933	0.619
GFDL-ESM4	[14]	105.	99.0	114.	6.18		1.26	2.78	1.38	0.377	0.288	0.735	0.897	0.517
IPSL-CM5A-LR	[14]	165.	150.	113.	11.7	0.515	-0.177	1.59	1.49	0.495	0.403	0.702	0.939	0.588
IPSL-CM6A-LR	[14]	115.	109.	113.	5.27	0.708	1.18	2.68	1.20	0.327	0.352	0.781	0.896	0.542
MeanCMIP5	[14]	121.	115.	114.	6.65		0.111	1.39	1.14	0.547	0.477	0.790	0.961	0.650
MeanCMIP6	[14]	116.	110.	114.	6.26		0.574	1.41	0.981	0.494	0.502	0.799	0.965	0.652
MIROC-ESM	[14]	129.	118.	102.	9.04	11.4	0.129	1.17	0.931	0.572	0.522	0.826	0.956	0.879
MIROC-ESM2L	[14]	116.	104.	113.	9.90	0.119	0.396	1.90	1.27	0.463	0.435	0.767	0.920	0.604
MPI-ESM-LR	[14]	169.	159.	104.	8.91	9.81	-0.0111	1.95	1.99	0.409	0.379	0.828	0.920	0.543
MPI-ESM1.2-LR	[14]	141.	133.	104.	6.89	9.81	1.36	2.36	1.29	0.402	0.371	0.715	0.930	0.558
NorESM1-ME	[14]	129.	120.	114.	7.82		0.386	1.86	1.25	0.387	0.456	0.761	0.856	0.583
NorESM2-LM	[14]	107.	97.5	114.	7.59		-0.0828	1.63	1.31	0.443	0.472	0.791	0.938	0.623
UK-HadGEM2-ES	[14]	137.	130.	113.	6.93	0.848	0.602	2.01	1.10	0.389	0.388	0.820	0.855	0.568
UKESM1-0-LL	[14]	126.	119.	113.	7.06	0.825	0.387	1.77	1.16	0.436	0.419	0.791	0.924	0.598





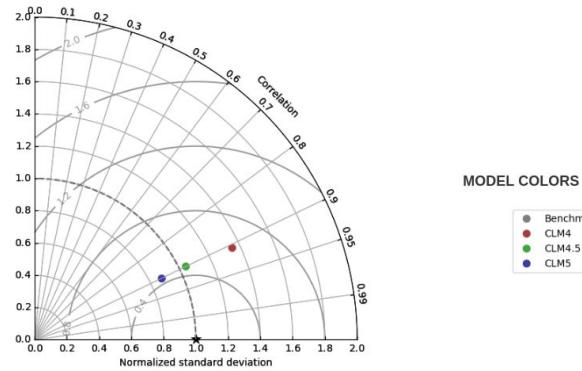
ILAMB Graphical Diagnostics



ILAMB Graphical Diagnostics



SPATIAL TAYLOR DIAGRAM



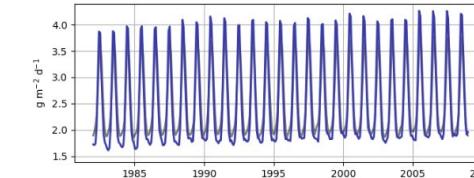
MODEL COLORS

- Benchmark
- CLM4
- CLM4.5
- CLM5

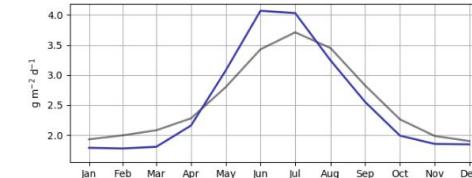
Spatially integrated regional mean

MODEL COLORS

REGIONAL MEAN



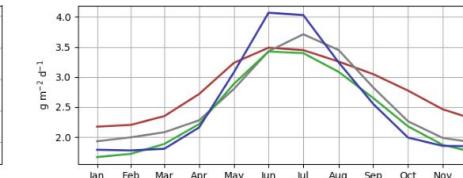
ANNUAL CYCLE

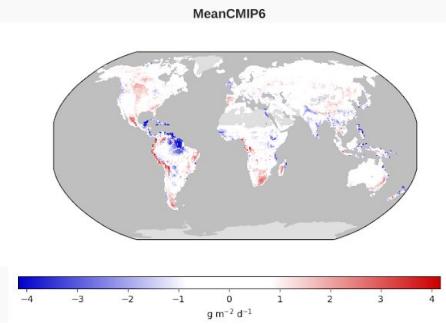
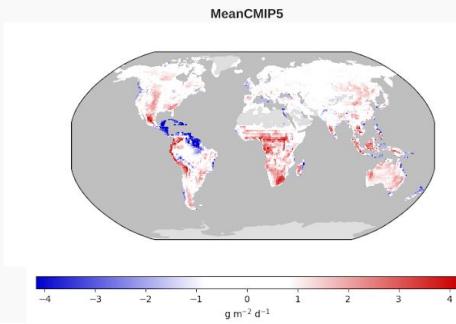
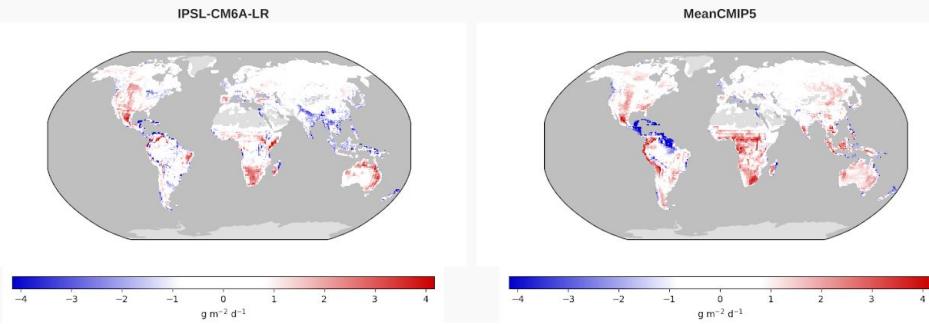
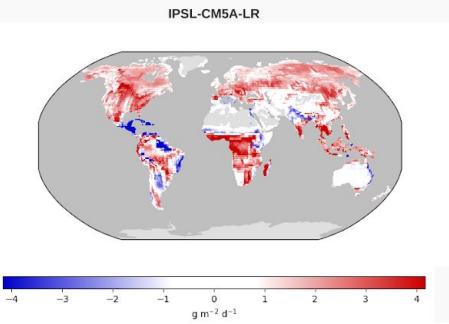
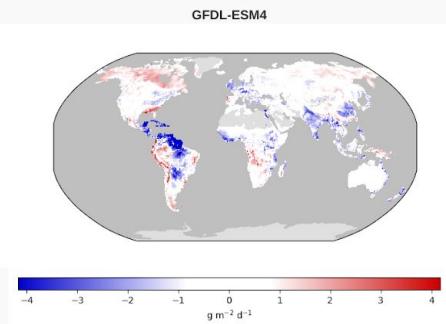
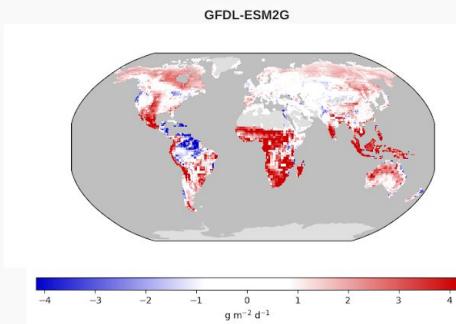
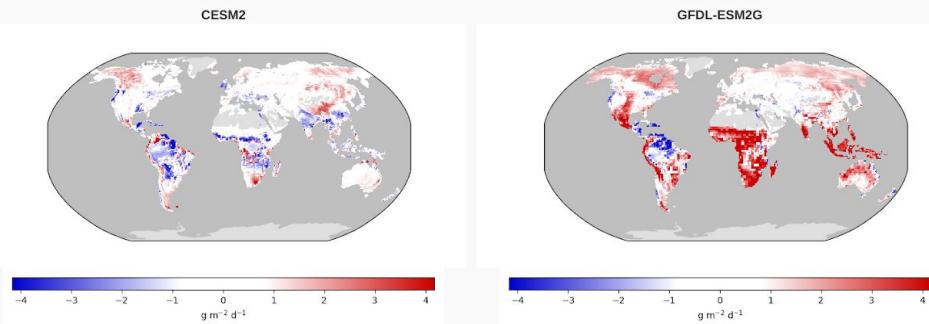
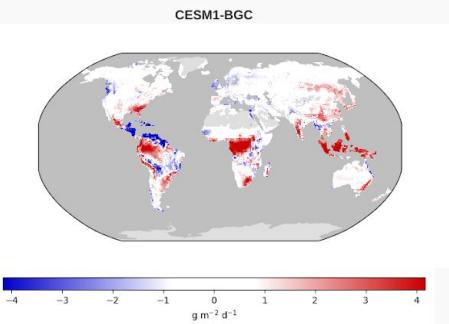
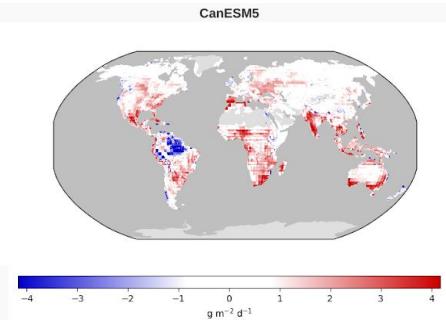
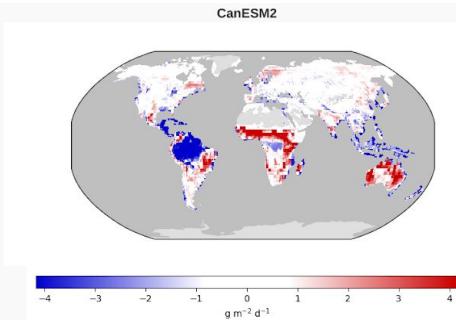
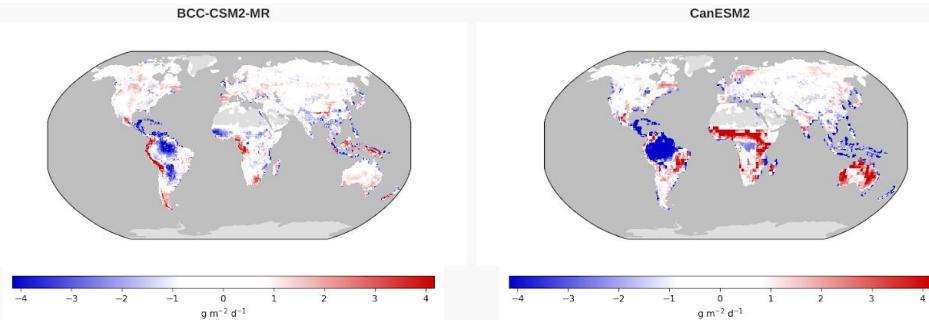
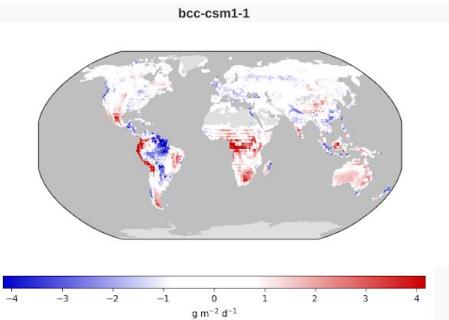


MONTHLY ANOMALY

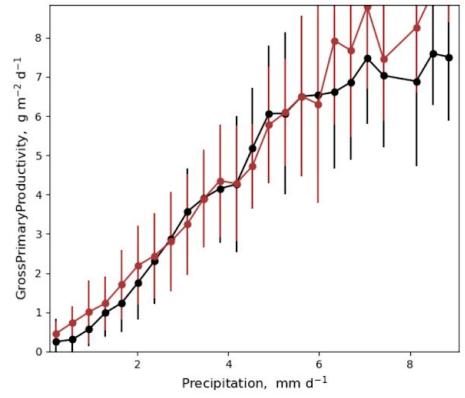
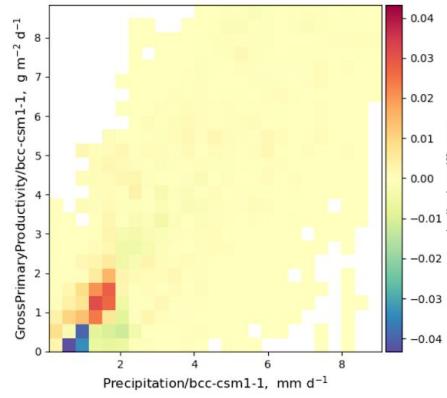
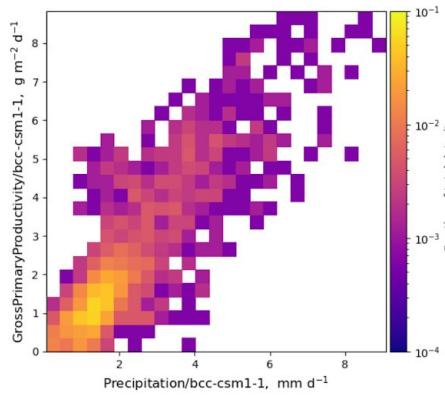
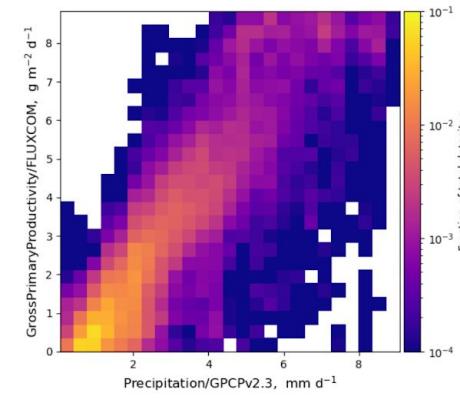


ANNUAL CYCLE





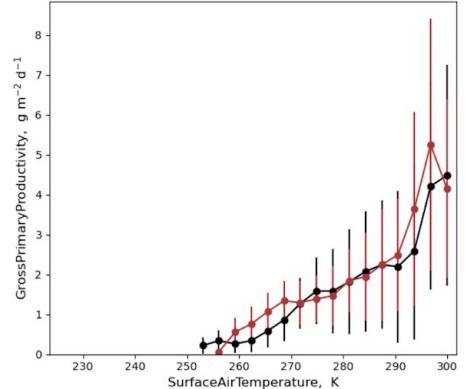
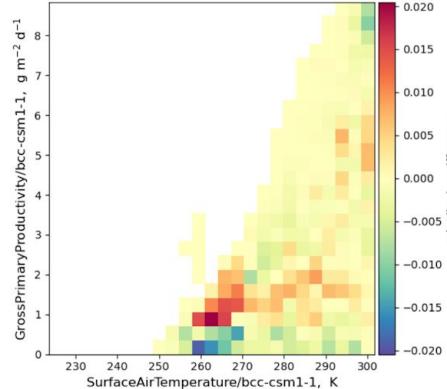
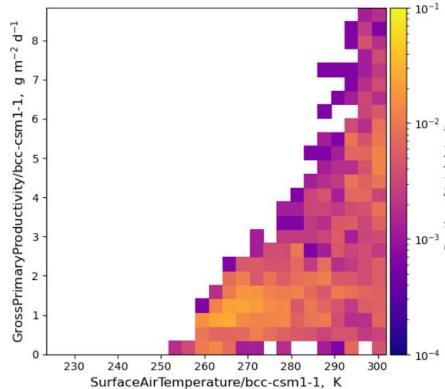
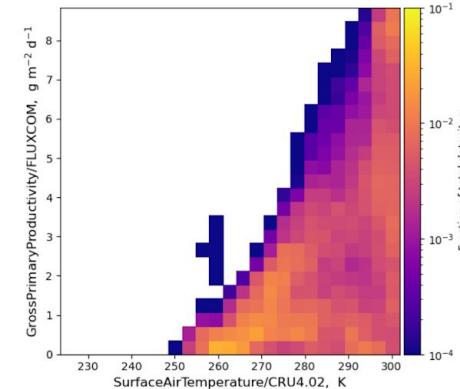
● Precipitation/GPCPv2.3



● SurfaceDownwardSWRadiation/CERESd4.1

● SurfaceNetSWRadiation/CERESd4.1

● SurfaceAirTemperature/CRU4.02





ILAMB Data Collections

- ILAMB hosts thematic data collections to support model benchmarking that can be downloaded using “**ilamb-fetch**” tool.
- Currently three collections are supported:
 - ILAMB-Data, ABoVE-Data, NGEEA-Data

```
ilamb-fetch --local_root=ILAMB/DATA --collection=ABoVE-Data --no-check-certificate
```

- Data inventory: <https://ilamb.org/datasets.html>

