Projecting the Future of Life on Earth: Challenges in Earth System Modeling and Analysis

Forrest M. Hoffman (Oak Ridge National Laboratory)

U.S. DEPARTMENT OF ENERGY

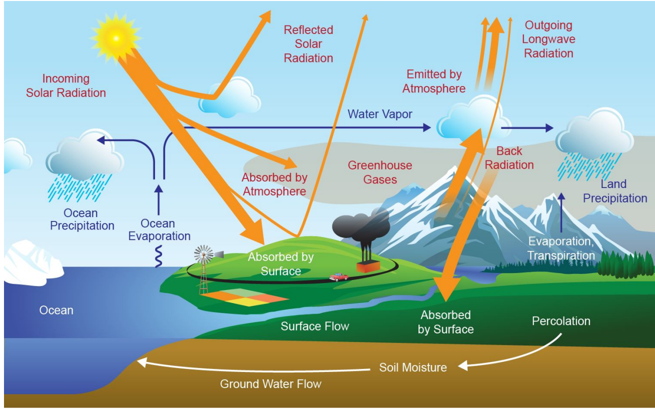
Office of Science

RUBISCO

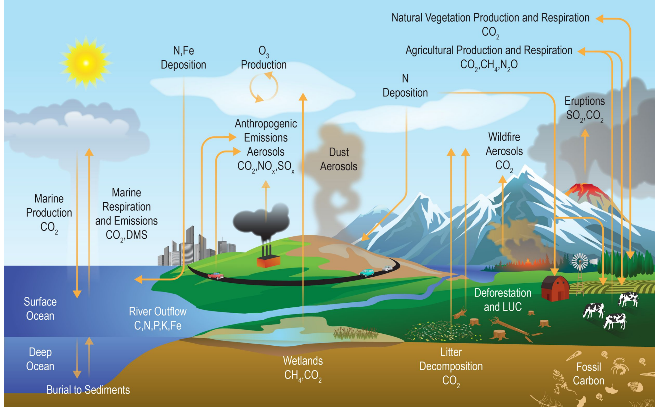
What is an Earth System Model?

An **Earth System Model (ESM)** is a coupled model that

- Solves differential equations of fluid motion and thermodynamics to obtain time and space dependent values for temperature, winds and currents, moisture and/or salinity and pressure in the atmosphere and ocean
- Combines component models of the atmosphere, ocean, land surface, sea ice, and land ice
- Closes the global carbon cycle by simulating processes and feedbacks of vegetation and marine ecology and biogeochemistry, land use change, and (increasingly) human system processes



Energy and Water Cycles



Carbon and Biogeochemical Cycles

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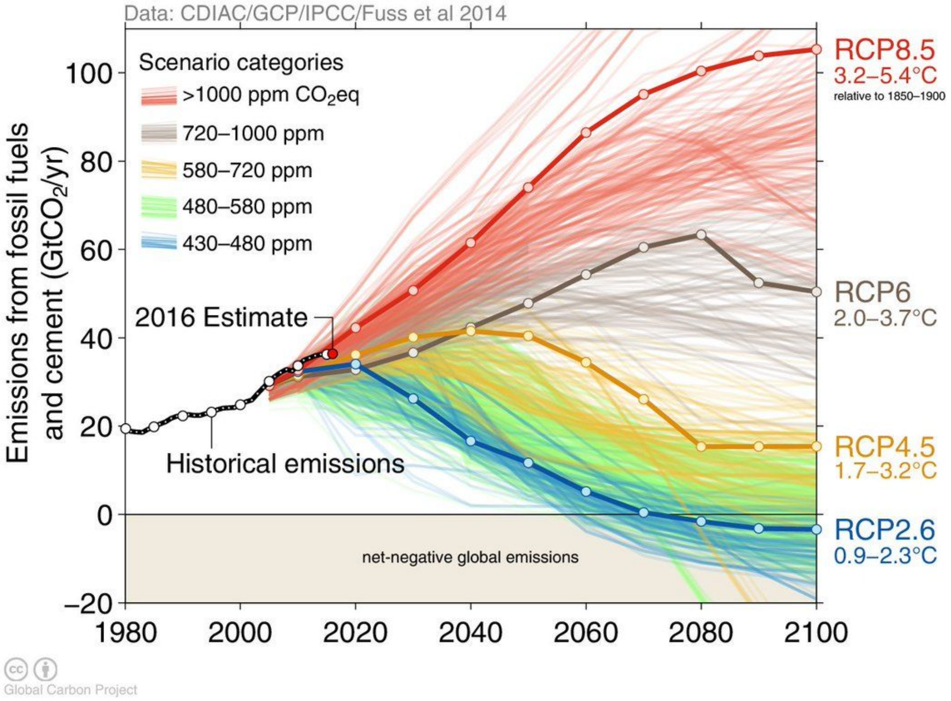
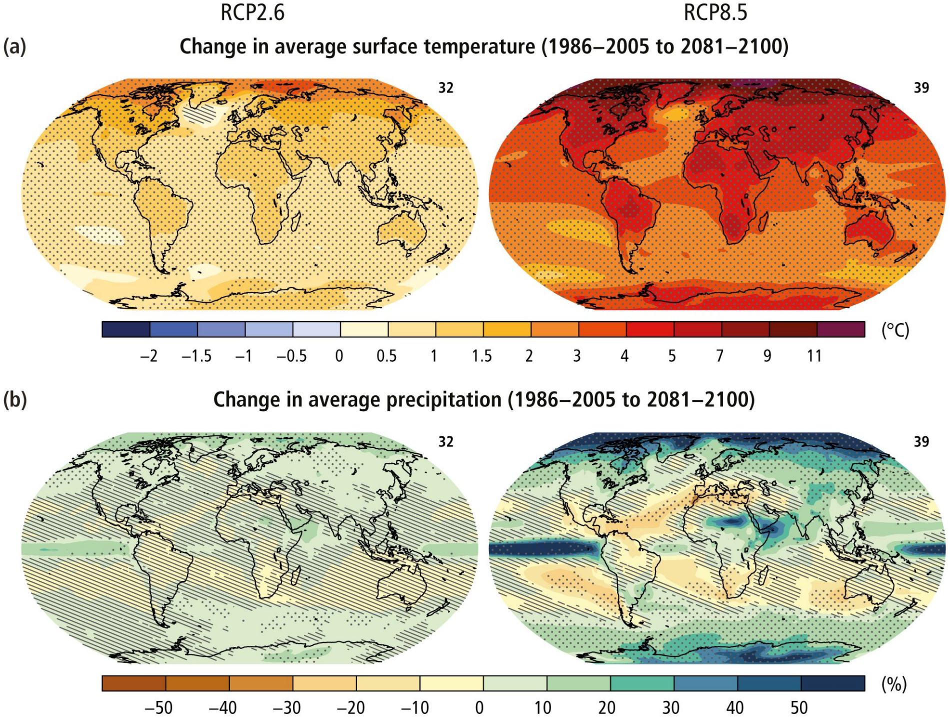
ESMs project future changes in the climate system

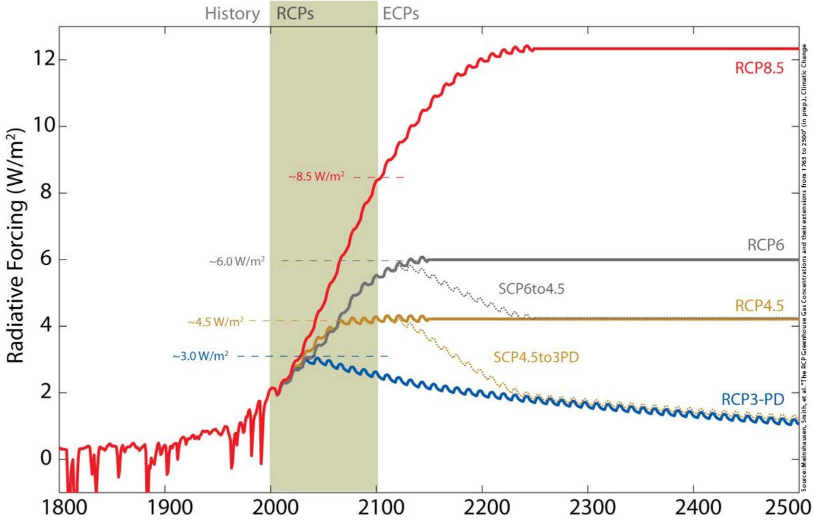




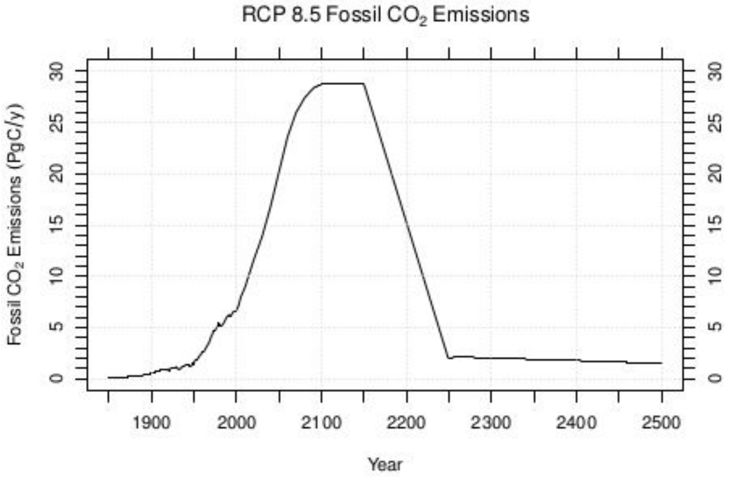
From IPCC AR5 WG1 Summary for Policymakers (SPM)

Science Question: To what degree do the effects of climate change due to warming and CO_2 fertilization in isolation combine linearly?

Radiative Forcing for RCPs and ECPs



Meinshausen et al. (2011) extended RCP forcings out to 2500



Simulation Identifier	Radiative Coupling: CO_2	Radiative Coupling: Other GHG & aerosols	Biogeochemical Coupling: CO_2	Biogeochemical Coupling: Nitrogen deposition	Biogeochemical Coupling: Land use	Experiment Name
RAD	✓	✓	–	–	–	bcrd
BGC	–	–	✓	✓	–	bdrcs.pftcon
FC	✓	✓	✓	✓	–	bdrd.pftcon

✓ Transient anthropogenic forcing

– Constant pre-industrial (1850) forcing

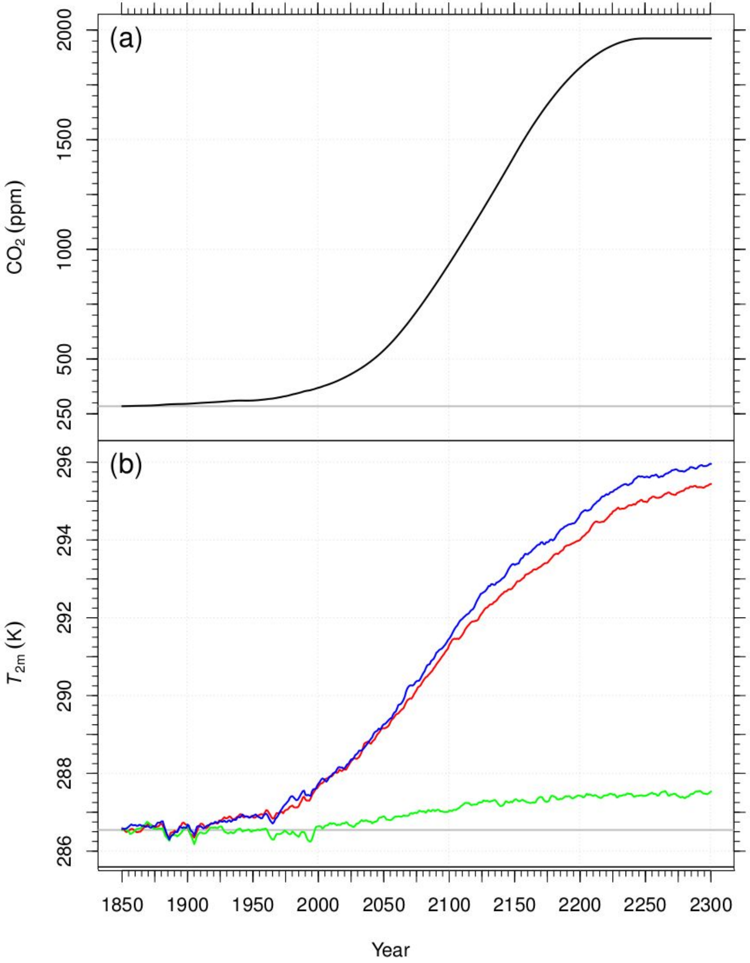
$$\Delta C_O = \beta_O \, \Delta CO_2 + \gamma_O \, \Delta T$$

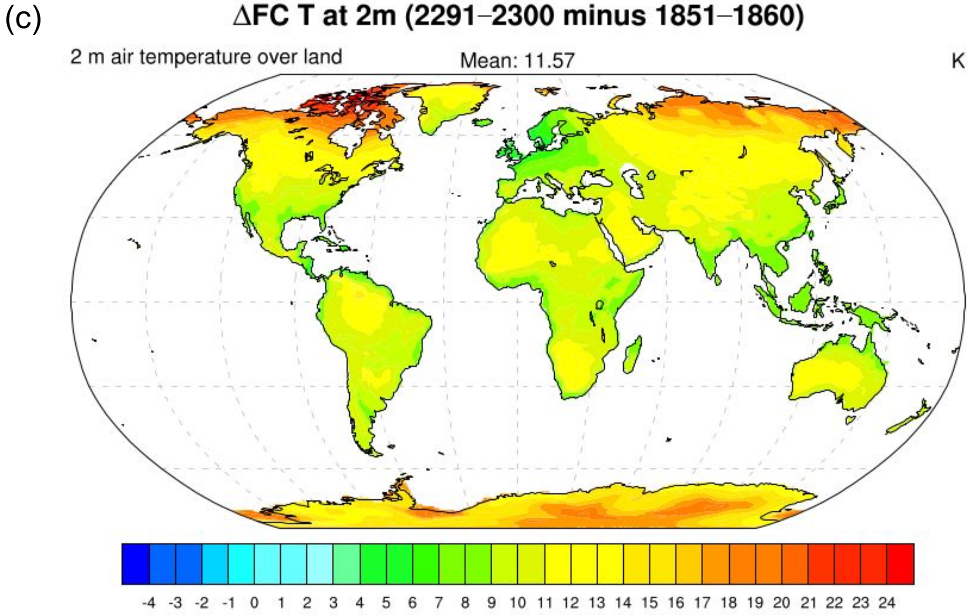
$$\Delta C_L = \beta_L \, \Delta CO_2 + \gamma_L \, \Delta T$$

$$g = \frac{-\alpha \left(\gamma_O + \gamma_L\right)}{\left(m + \beta_O + \beta_L\right)}$$

From Friedlingstein et al. (2006).

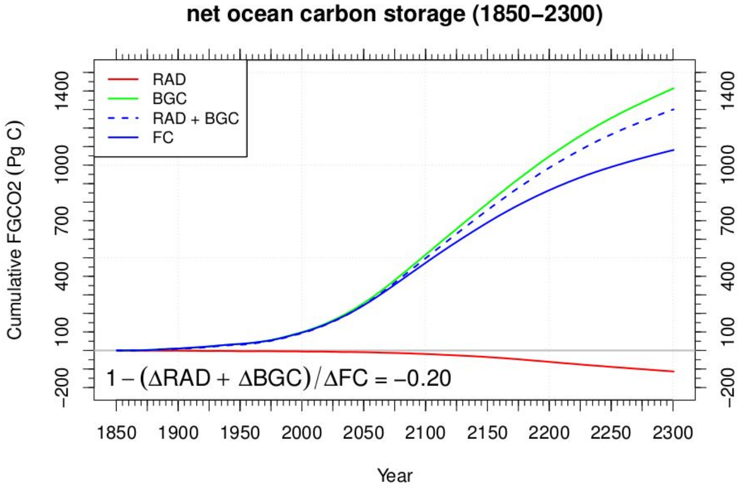
Climate–Carbon Cycle Drivers (1850–2300)



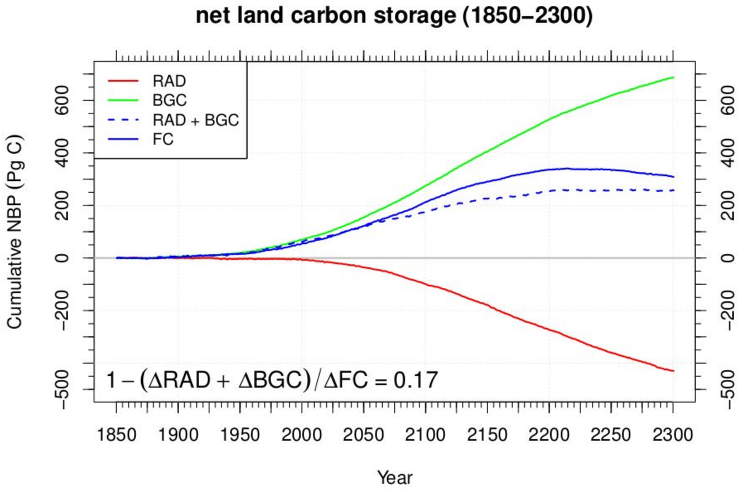


(a) Prescribed atmospheric CO_2 mole fraction was stabilized at 1962 ppm around 2250. (b) 2 m air temperature increased by 9.4°C in **FC**, 8.9°C in **RAD**, and 1.0°C in **BGC** simulations. (c) Mean air temperature over land increased by 11.6°C in the **FC** simulation and approached 25°C at high latitudes.

Net Ocean and Land Carbon Uptake (1850–2300)



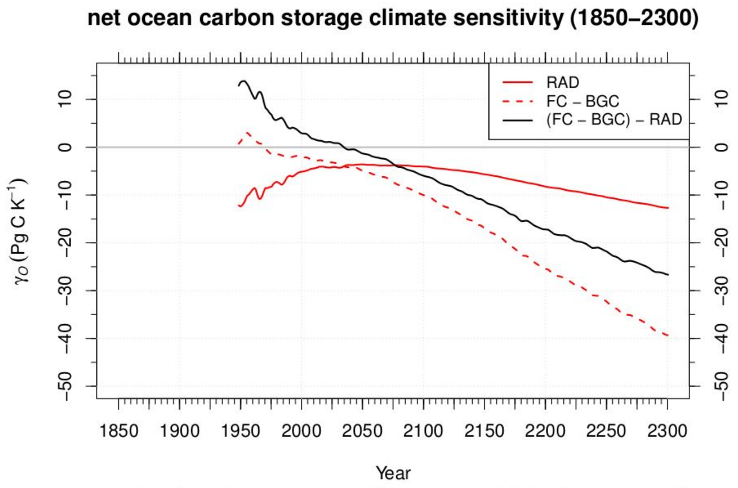
Net ocean carbon storage has a nonlinear response that Schwinger et al. (2014) attributed to surface stratification under climate change that restricted C penetration into intermediate and deep waters.



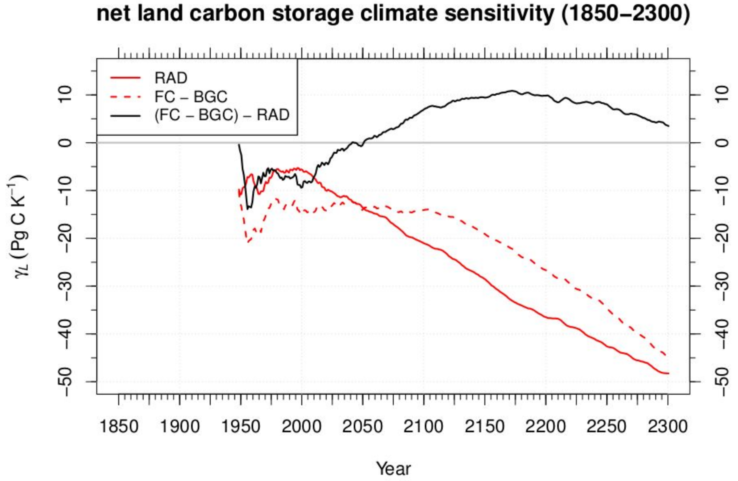
Net land carbon storage also has a nonlinear response, of opposite sign, that has not been explored in ESMs, although Zickfeld et al. (2011) explored similar nonlinear responses in an EMIC. It is driven by larger than expected productivity increases due to positive hydrological and nitrogen mineralization feedbacks.

Ocean and Land Climate–Carbon Sensitivities

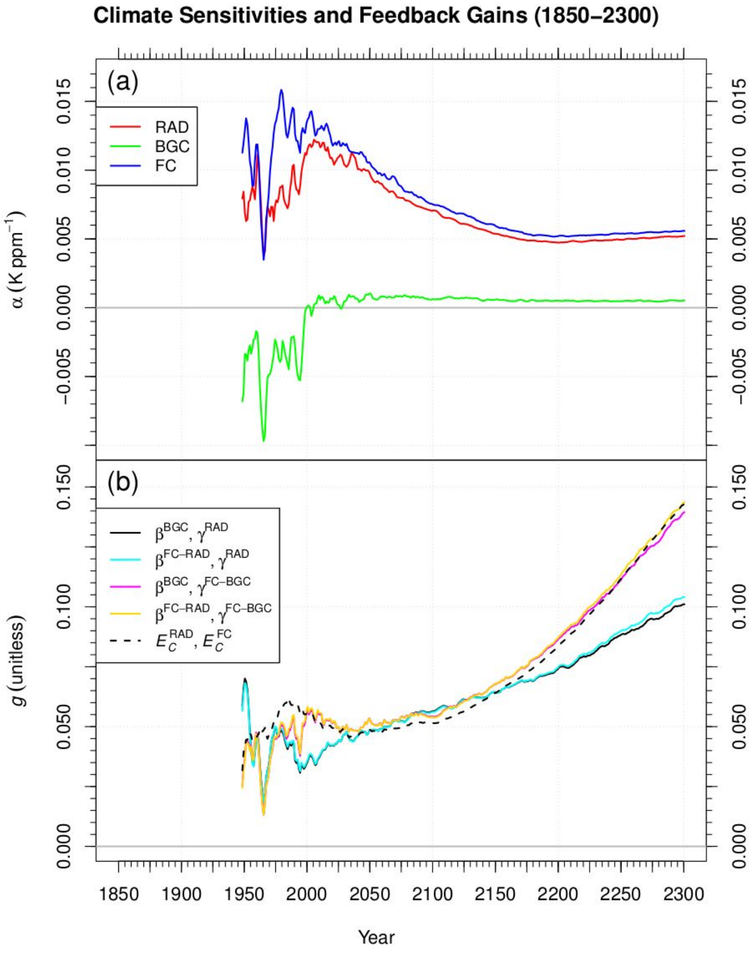
The difference between the net ocean carbon storage climate sensitivities, γ_O^{RAD} and γ_O^{FC-BGC}, was nearly −27 Pg C K^{-1} and continued to diverge at the end of the 23rd century.



The difference between the net land carbon storage climate sensitivities, γ_L^{RAD} and γ_L^{FC-BGC}, peaked at about 10 Pg C K^{-1} around 2175 and ended at about 4 Pg C K^{-1} at 2300.



Climate Sensitivities and Climate–Carbon Cycle Gains

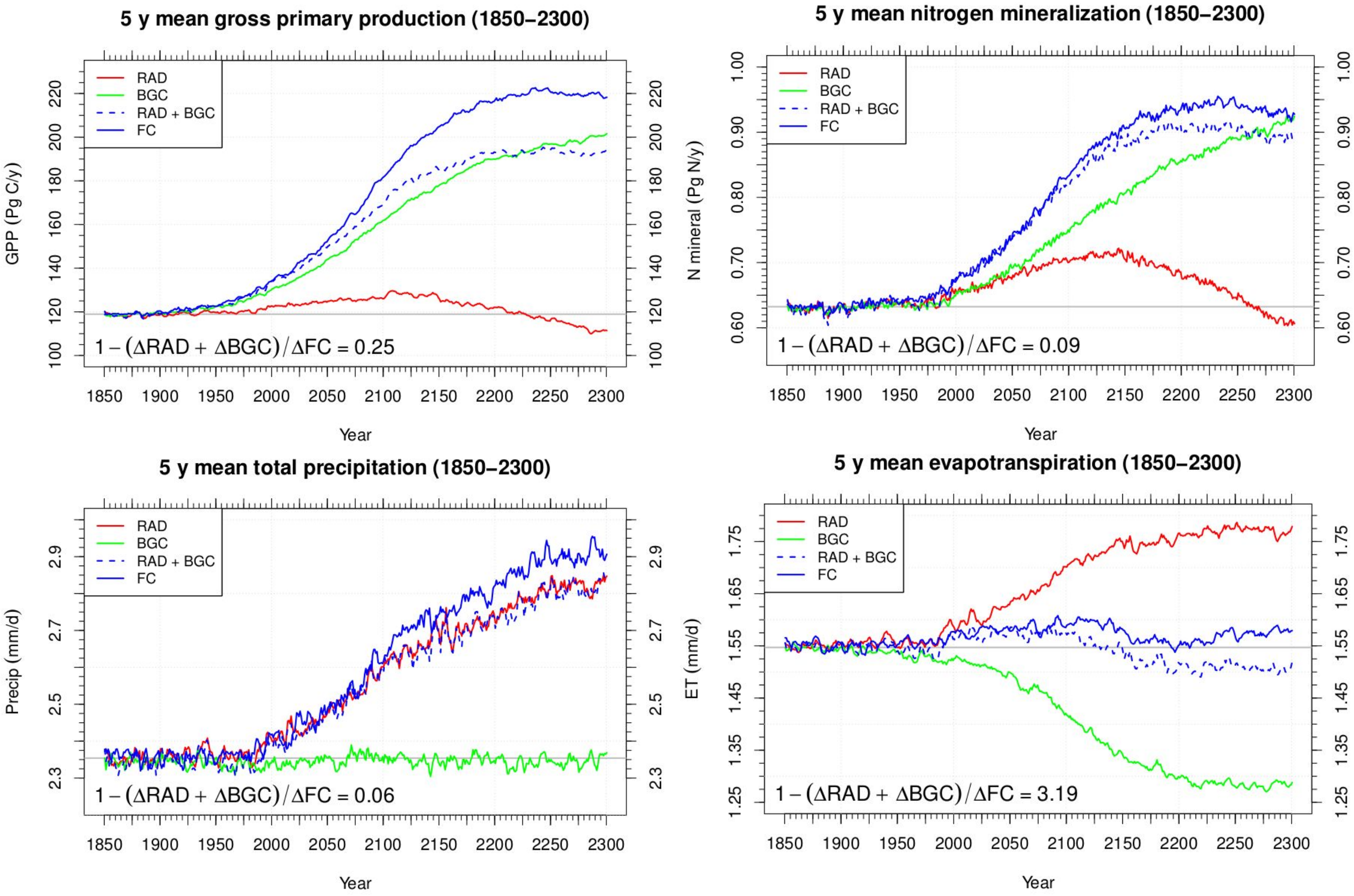


The climate sensitivity, α, for the **FC** simulation was about 0.0056 K ppm^{-1} at the end of the 23rd century.

The climate–carbon cycle gain* (*g*) clustered around two different values, depending on the method and experiments used to calculate it, and at 2300 was 42% higher when estimated from sensitivity parameters derived from (**FC** – **BGC**) than from RAD.

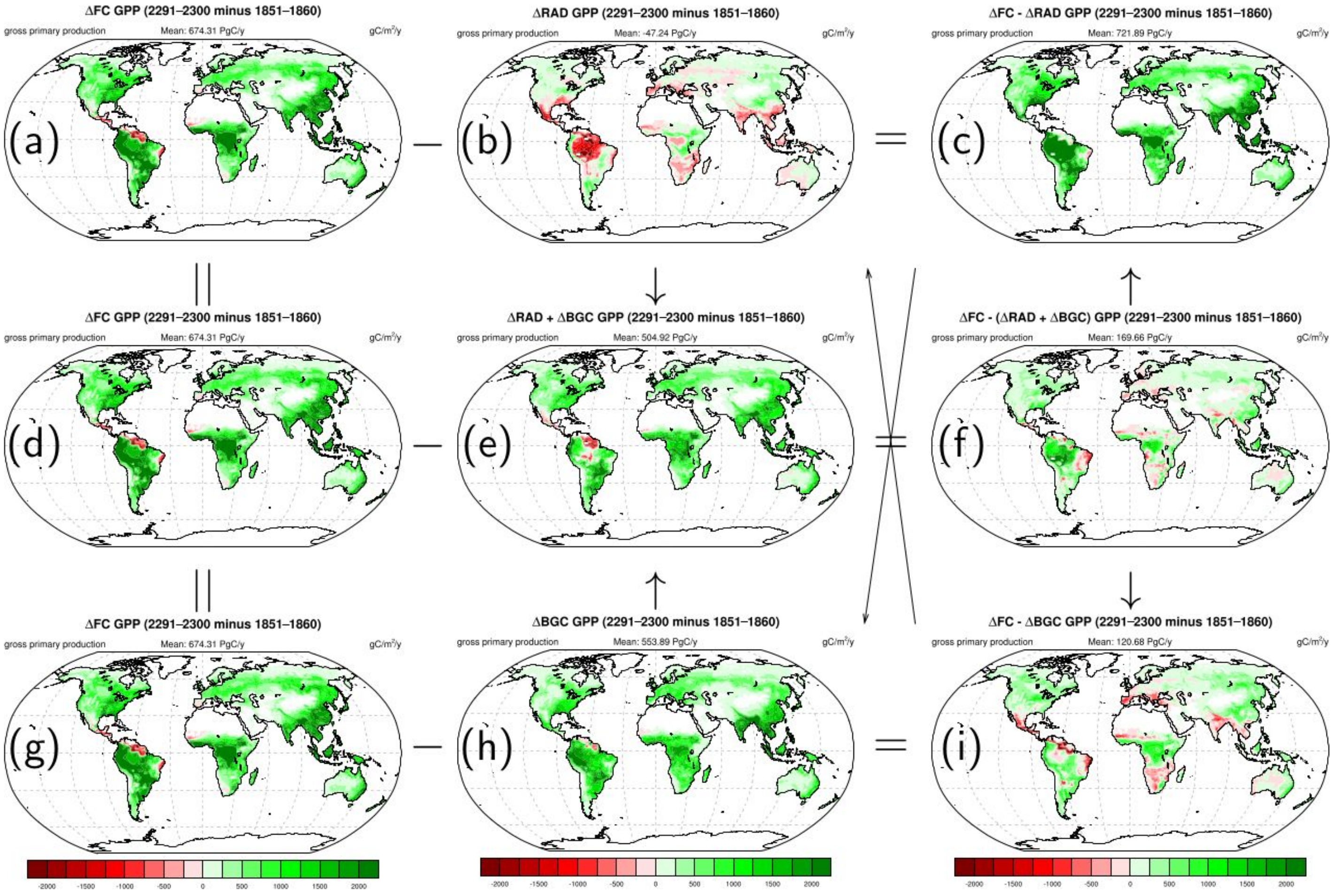
*This gain included effects of aerosols and other greenhouse gases.

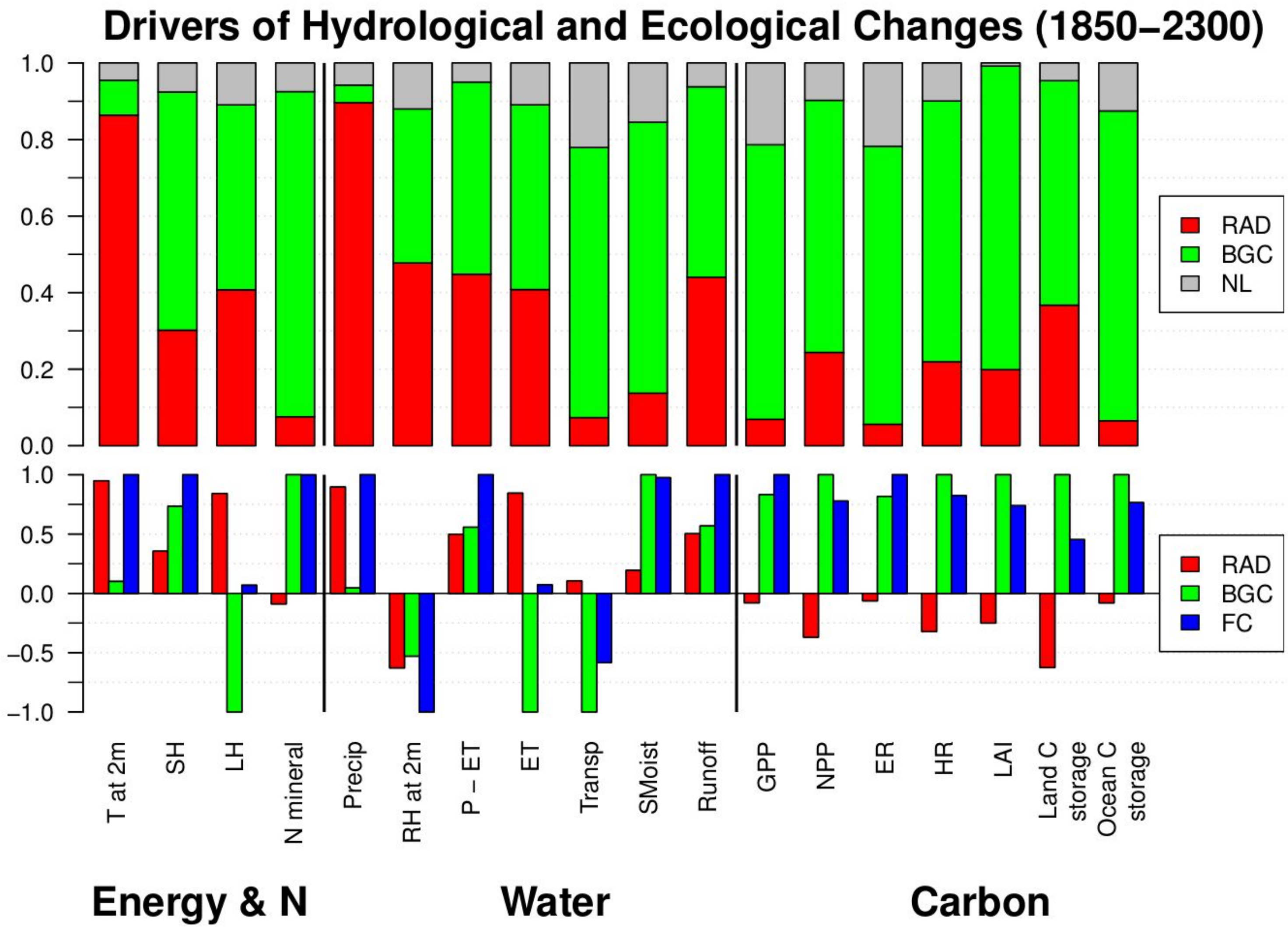
Drivers of Nonlinear Terrestrial Uptake Responses



Enhanced gross primary production (GPP) and higher rates of N mineralization, driven by excess precipitation increases and reduced evapotranspiration, led to the nonlinear C uptake response on land under simultaneous climate change and elevated CO_2 levels.

Nonlinear GPP Responses Across Model Experiments




Drivers of Hydrological and Ecological Changes (1850−2300)
1.0
0.8
0.6
0.4
0.2
0.0
RAD
BGC
NL
1.0
0.5
0.0
−0.5
−1.0
RAD
BGC
FC
T at 2m
SH
LH
N mineral
Precip
RH at 2m
P − ET
ET
Transp
SMoist
Runoff
GPP
NPP
ER
HR
LAI
Land C storage
Ocean C storage
Energy & N
Water
Carbon

Science Question: To what degree do the effects of climate change due to warming and CO_2 fertilization in isolation combine linearly?

- **RAD** simulations yielded a net ocean carbon storage climate sensitivity (γ_O) that was weaker and a net land carbon storage sensitivity (γ_L) that was stronger than those diagnosed from **FC** and **BGC** simulations.
  - For the ocean, the nonlinearity was associated with warming-induced weakening of ocean circulation and mixing, which limited exchange of dissolved inorganic carbon between surface and deeper water masses.
  - For the land, the nonlinearity was associated with strong gains in gross primary production in the **FC** simulation, driven by enhancements in the hydrological cycle and increased nutrient availability.
- The feedback gain* (*g*) at 2300 was 42% higher when estimated from sensitivity parameters derived from (**FC** – **BGC**) than from **RAD**.
- We recommend deriving γ_O^{FC-BGC} and γ_L^{FC-BGC} in future studies.

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*This gain included effects of aerosols and other greenhouse gases.

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.

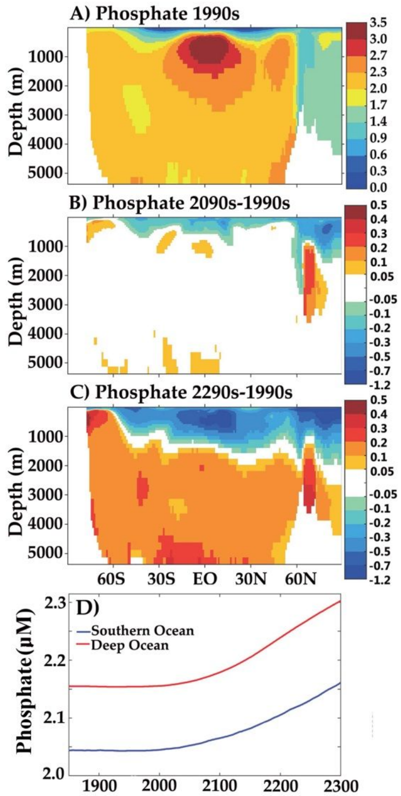

Figure: Antarctic trapping increases nutrient transfer to the deep ocean.

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

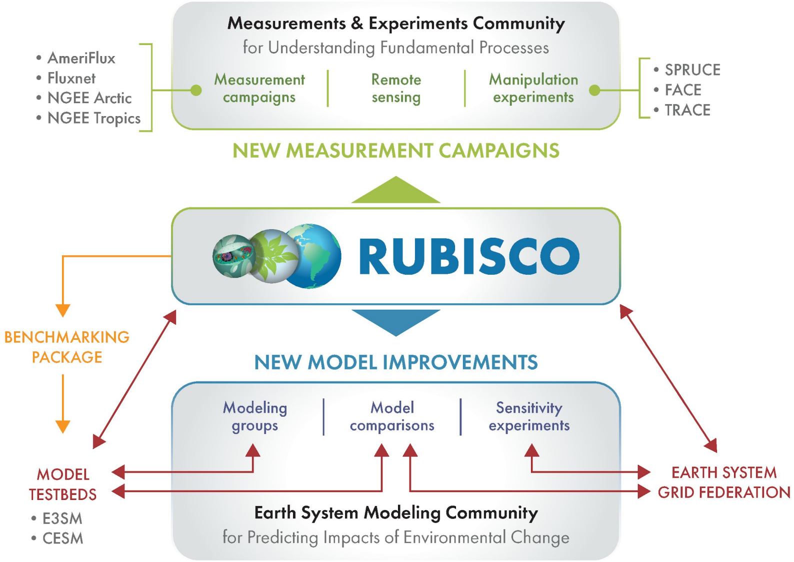
Forrest M. Hoffman (Laboratory Research Manager), William J. Riley (Senior Science Co-Lead), and James T. Randerson (Chief Scientist)

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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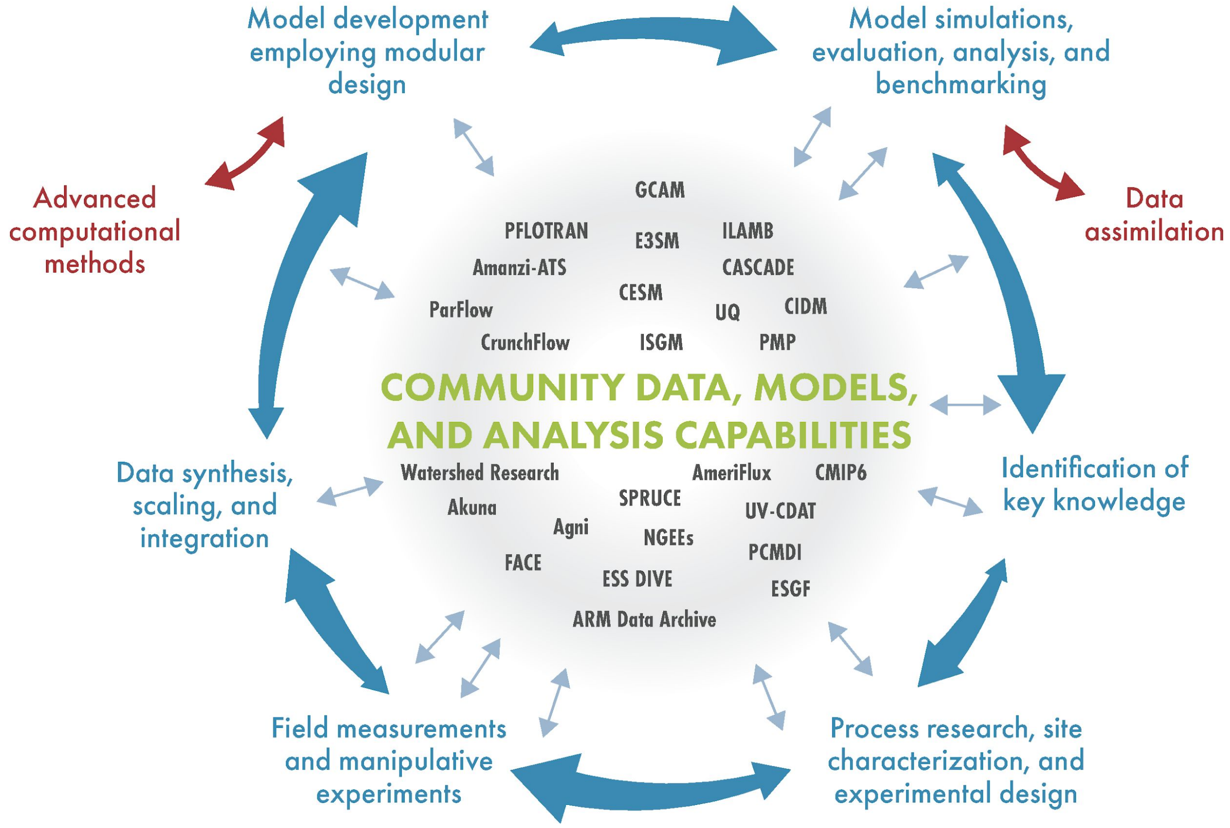
DOE’s Model-Data-Experiment Enterprise



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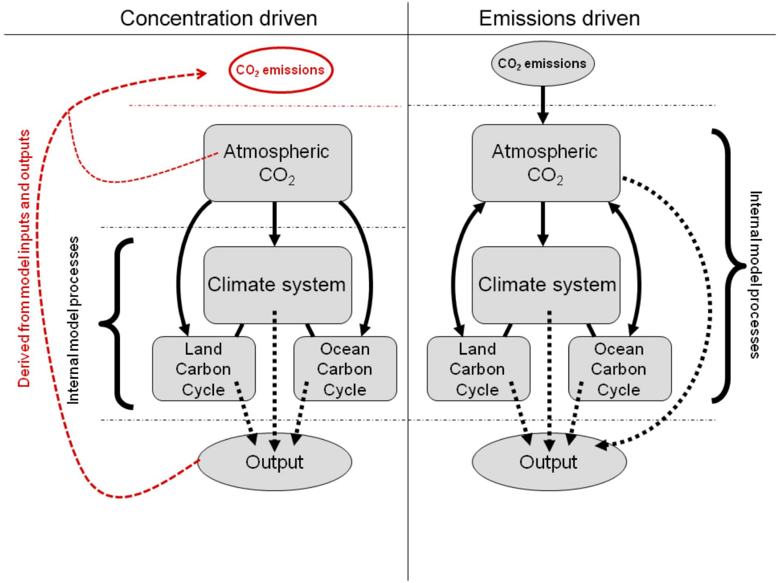
Coupled Carbon-Cycle Climate MIP (C4MIP) Experiments

	CO_2 input to radiation scheme	CO_2 input to carbon-cycle scheme	Reason
Fully coupled			Simulates the fully coupled system
'Biogeochemically' coupled 'esmFixClim'			Isolates the carbon-cycle response to CO_2 (β) for land and oceans
Radiatively coupled 'esmFdbk'			Isolates carbon-cycle response to climate change (γ) for land and for oceans

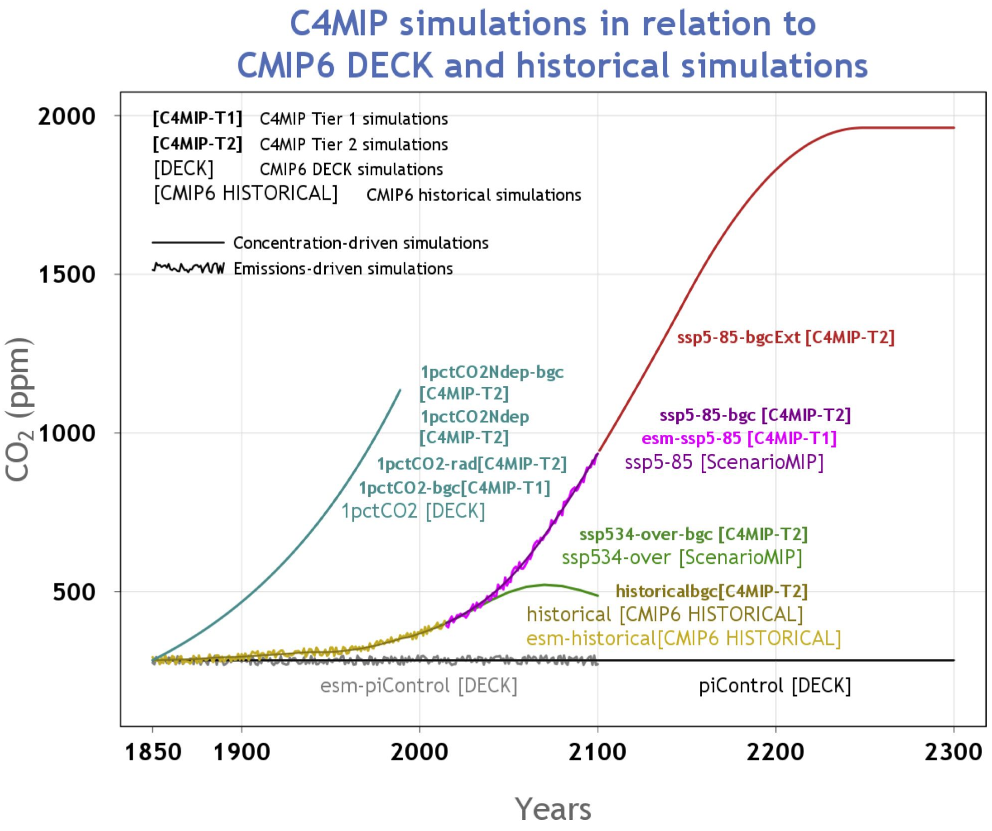
2 types of Experiments in C4MIP:

- Partially-coupled concentration-driven
- Fully-coupled emissions-driven



RUBISCO E3SM Experiments for CMIP6

- **Coupled Climate-Carbon Cycle MIP (C4MIP)**
  - 1% CO_2/yr idealized bgc
  - Emissions-driven (esm) control, historical, ssp5-85
  - Long-term fully and partially coupled concentration-driven experiments
- **Land Use MIP (LUMIP)**
- **Land Surface, Snow and Soil Moisture MIP (LS3MIP)**



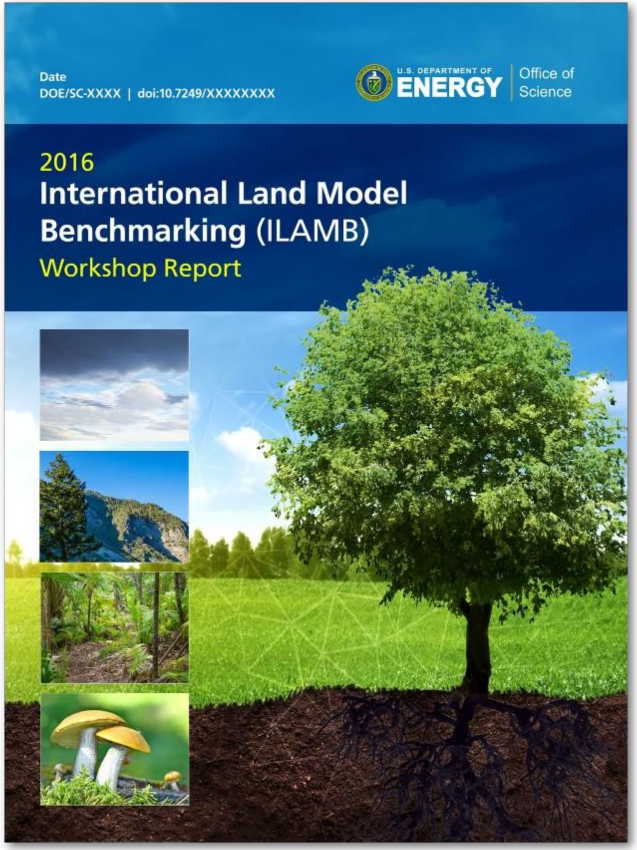
International Land Model Benchmarking (ILAMB)

ILAMB is a community coordination activity to

- Develop internationally accepted benchmarks
- Promote the use of these benchmarks
- Strengthen linkages between experimental, remote sensing, and climate modeling communities
- Support the design and development of open source benchmarking tools

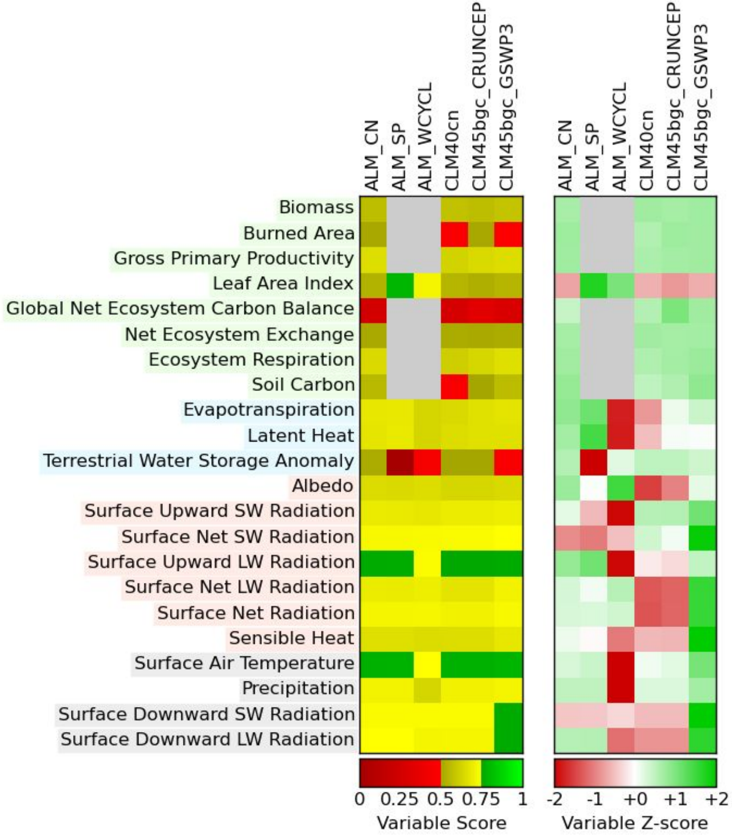
Second US ILAMB Workshop, May 16–18, 2016

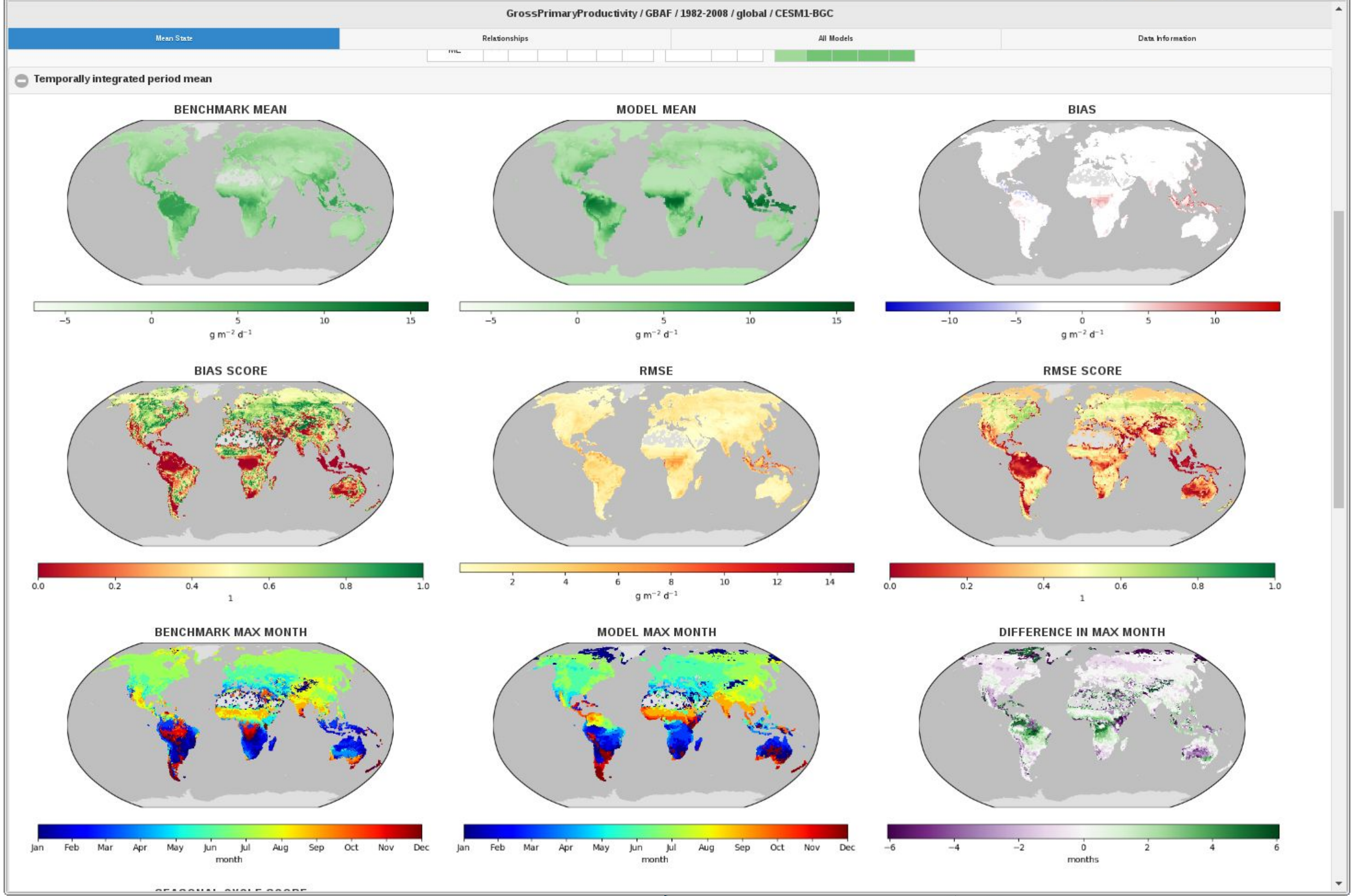
- 60+ participants from Australia, Japan, China, Germany, Sweden, Netherlands, UK, and US
- 10 modeling centers represented
- ~25 remote attendees at any time
- Workshop report identifies priorities and approaches



Development of ILAMB Packages

- **ILAMBv1** released at 2015 AGU Fall Meeting Town Hall, doi:10.18139/ILAMB.v001.00/1251597
- **ILAMBv2** released at 2016 ILAMB Workshop, doi:10.18139/ILAMB.v002.00/1251621
- Actively being used for E3SM and CESM evaluation during development
- Employed to evaluate CMIP5 models
- Models are scored based on statistical comparisons (bias, RMS error, phase, amplitude, spatial distribution, Taylor scores)
- Functional response metrics




GrossPrimaryProductivity / GBAF / 1982-2008 / global / CESM1-BGC
Mean State
Relationships
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Data Information
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BENCHMARK MEAN
MODEL MEAN
BIAS
g m^{-2} d^{-1}
BIAS SCORE
RMSE
RMSE SCORE
BENCHMARK MAX MONTH
MODEL MAX MONTH
DIFFERENCE IN MAX MONTH
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
month
months

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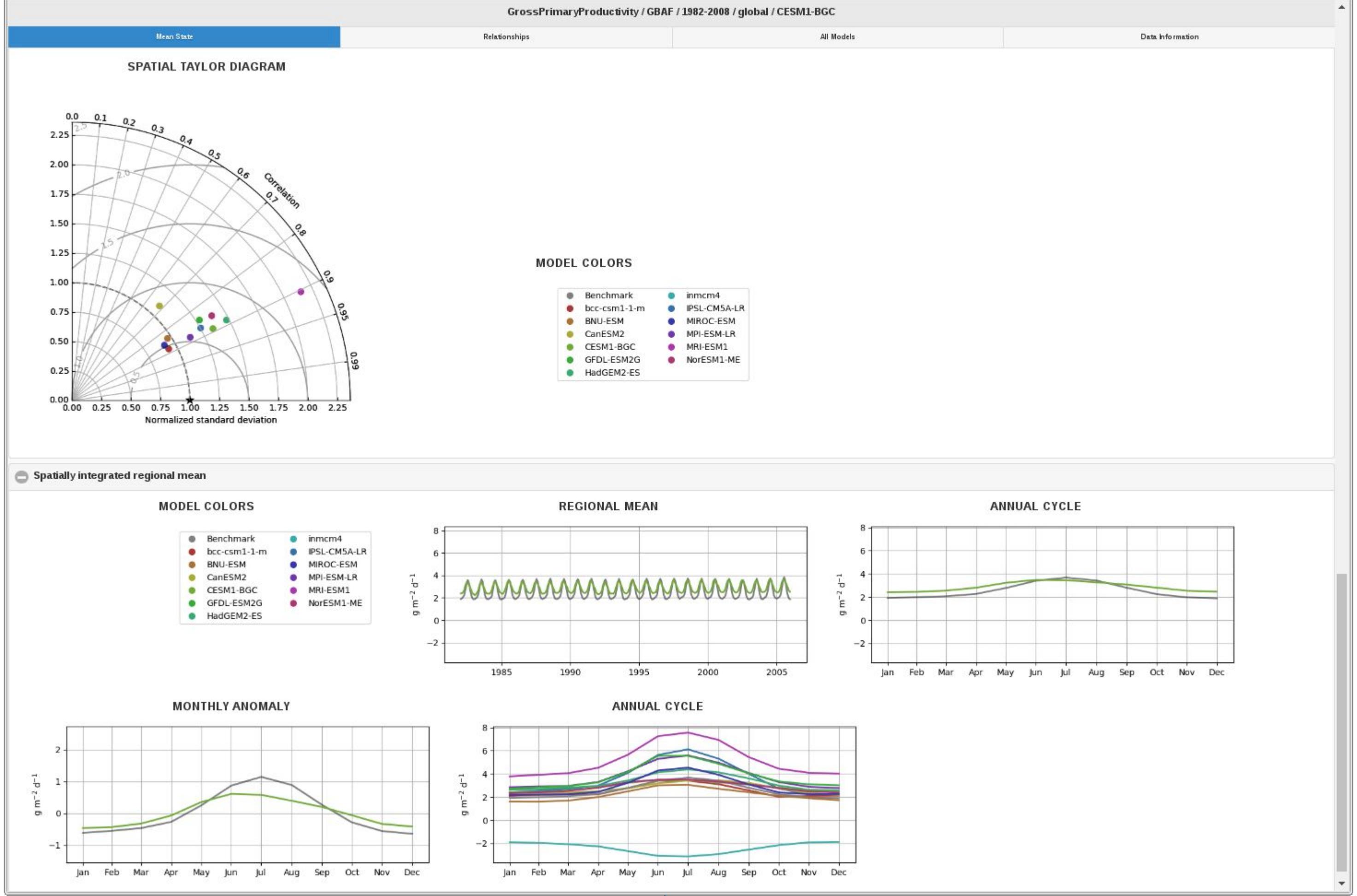

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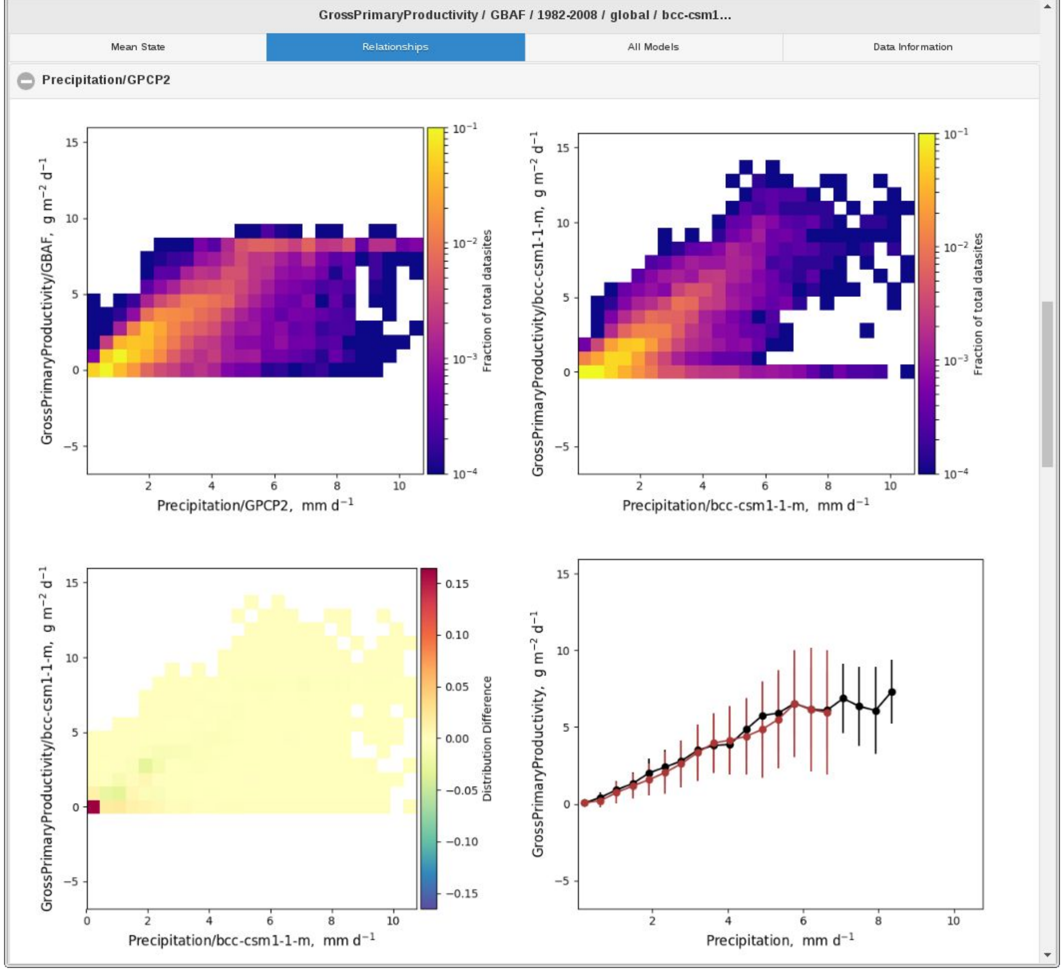
GrossPrimaryProductivity / GBAF / 1982-2008 / global / bcc-csm1...
Mean State
Relationships
All Models
Data Information
Precipitation/GPCP2
GrossPrimaryProductivity/GBAF, g m^{-2} d^{-1}
Precipitation/GPCP2, mm d^{-1}
Fraction of total datasites
GrossPrimaryProductivity/bcc-csm1-1-m, g m^{-2} d^{-1}
Precipitation/bcc-csm1-1-m, mm d^{-1}
Distribution Difference
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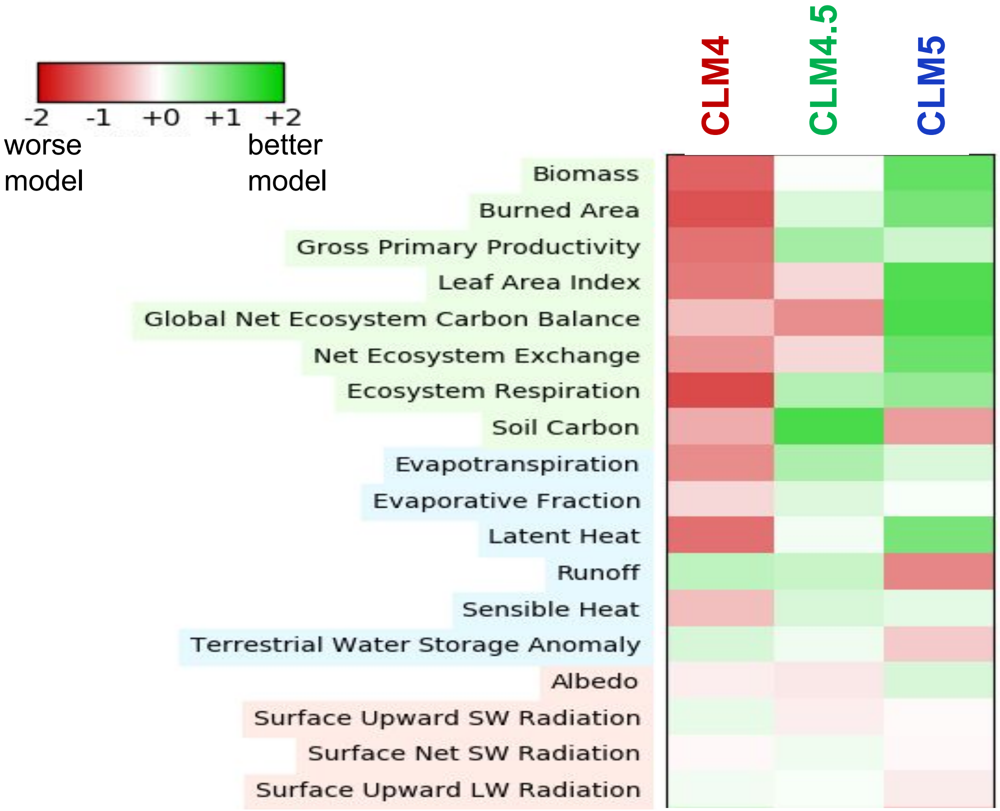
Precipitation, mm d^{-1}

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)

Lawrence et al., in prep

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International Ocean Model Benchmarking (IOMB) Package

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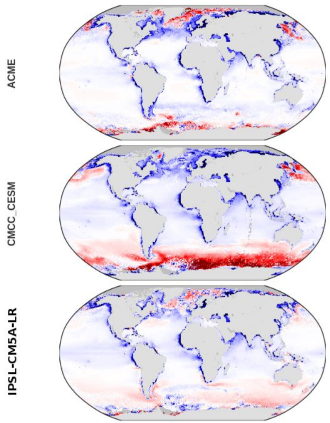
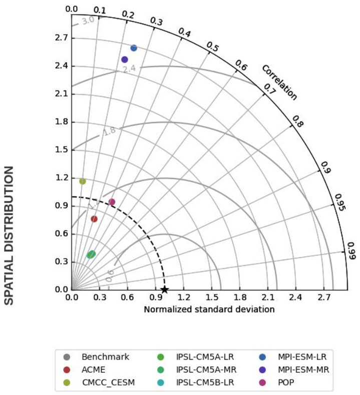
- Evaluates ocean biogeochemistry results compared with observations (global, point, ship tracks)
- Scores model performance across a wide range of independent benchmark data
- Leverages ILAMB code base, also runs in parallel
- Built on python and open standards
- Is also open source and will be released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

Chlorophyll / SeaWIFS

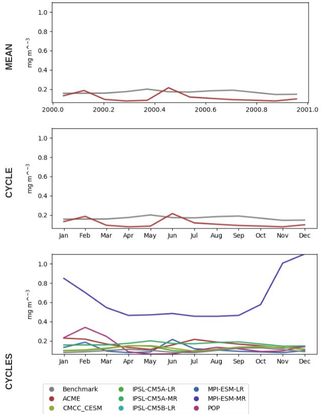
Bias

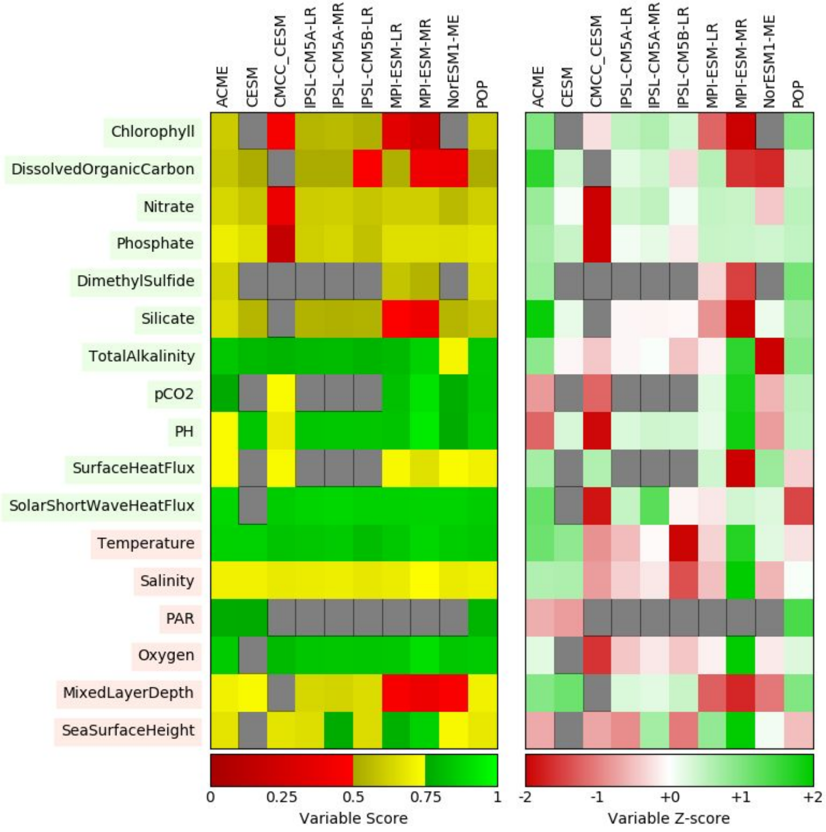


Spatial Distribution



Annual & Seasonal Cycles





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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

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

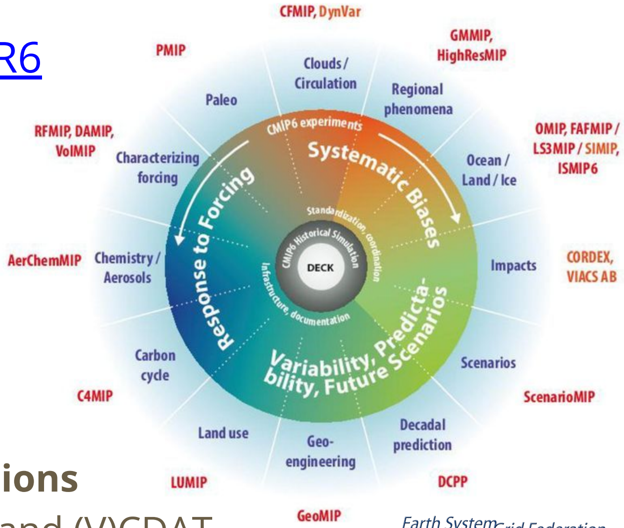
Model–Data Integration Theme

- 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>

Coupled Model Intercomparison Project

- 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: 2 PB disk storage** and **interactive computing resources**
  - *Richard Gerber, Rollin Thomas, Jialin Liu*

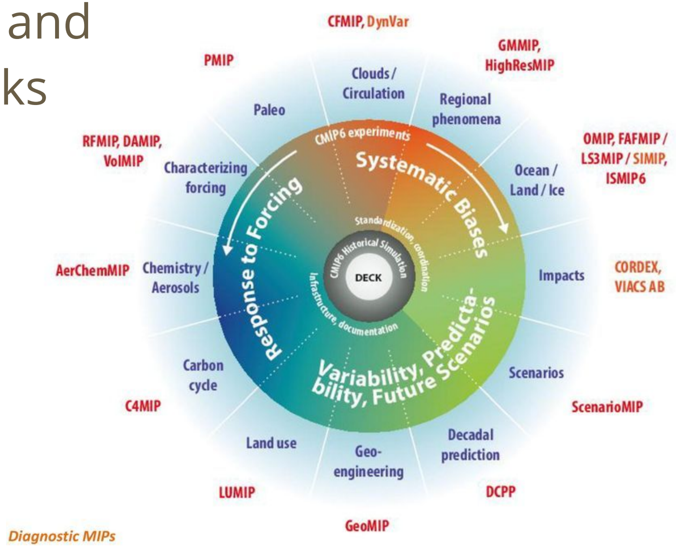


/global/cscratch1/sd/cmip6

RGMA CMIP6 Analysis and Hackathon

WCRP World Climate Research Programme CMIP6

- 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



DOE CMIP6 Data Inventory at NERSC

Updated Fri Jul 19 07:31:06 PDT 2019

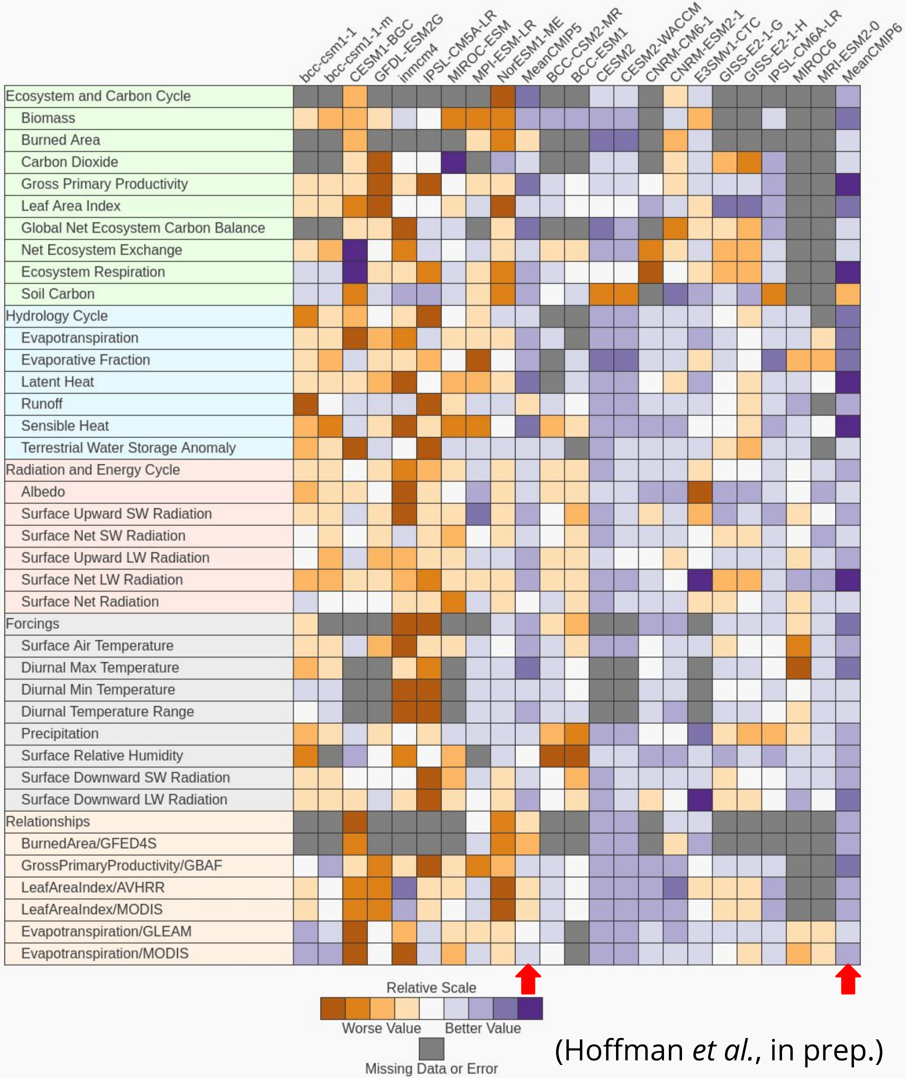
Model	C4MIP			CMIP									HighResMIP						ScenarioMIP				Model Total
	1pctCO2-bgc	1pctCO2-rad	esm-ssp585	1pctCO2	abrupt-4xCO2	amip	esm-hist	esm-piControl	esm-piControl-spinup	historical	piControl	piControl-spinup	control-1950	highres-future	highresSST-future	highresSST-present	hist-1950	spinup-1950	ssp126	ssp245	ssp370	ssp585	
AWI-CM-1-0-HR													1 / 0 10 / 0 4 GB				3 / 0 18 / 0 4 GB	1 / 0 1 / 0 0 GB					5 / 0 29 / 0 8 GB
AWI-CM-1-0-LR													1 / 0 10 / 0 4 GB				3 / 0 18 / 0 3 GB	1 / 0 1 / 0 0 GB					5 / 0 29 / 0 7 GB
AWI-CM-1-1-MR				120 / 120 3891 / 8656 2532 GB	120 / 120 8656 / 8656 5833 GB					567 / 600 42024 / 47410 19732 GB	50 / 50 25000 / 25000 10853 GB												857 / 890 79571 / 89722 38950 GB
BCC-CSM2-MR	122 / 146 292 / 336 360 GB	130 / 146 279 / 336 329 GB	205 / 229 7191 / 8451 6070 GB	77 / 154 149 / 344 173 GB	153 / 153 343 / 343 403 GB	286 / 462 4549 / 10224 3685 GB	601 / 602 4212 / 4218 5180 GB	153 / 153 558 / 558 806 GB		614 / 616 8205 / 8222 7906 GB	153 / 153 972 / 972 1598 GB								40 / 150 54 / 264 50 GB	66 / 150 107 / 264 103 GB	84 / 150 131 / 264 120 GB	225 / 225 8335 / 8335 6942 GB	2909 / 3489 35377 / 43131 33725 GB
BCC-ESM1				147 / 147 309 / 309 255 GB	137 / 137 299 / 299 255 GB	190 / 375 212 / 435 88 GB				555 / 555 1402 / 1402 1502 GB	142 / 142 409 / 409 366 GB												1171 / 1356 2631 / 2854 2466 GB
CAMS-CSM1-0				65 / 65 200 / 200 230 GB	65 / 65 200 / 200 230 GB	64 / 94 64 / 94 31 GB				67 / 67 217 / 217 254 GB									19 / 65 21 / 125 19 GB	33 / 65 51 / 126 48 GB	40 / 65 61 / 125 58 GB	65 / 65 125 / 125 130 GB	418 / 551 939 / 1212 1000 GB
CanESM5	298 / 411 862 / 1195 658 GB	300 / 411 875 / 1195 666 GB	897 / 1233 1836 / 2577 1107 GB	766 / 2044 1538 / 5474 1239 GB	744 / 744 2286 / 2286 1612 GB		3421 / 3443 10737 / 10803 8602 GB	386 / 386 5181 / 5202 3826 GB		13078 / 13444 40726 / 41812 31723 GB	708 / 708 7072 / 7204 5341 GB								1380 / 5403 1807 / 11135 867 GB	2410 / 5414 3895 / 10526 2036 GB	2546 / 5407 4090 / 10471 2108 GB	7231 / 7429 15518 / 16117 9632 GB	34165 / 46477 96423 / 125997 69417 GB
CESM2				770 / 931 1546 / 3452 1390 GB	865 / 865 1751 / 1751 2707 GB	339 / 610 588 / 1294 2245 GB				11297 / 19688 38735 / 58534 73052 GB	973 / 973 19476 / 19481 46121 GB												14244 / 23067 62096 / 84512 125515 GB
CESM2-WACCM				749 / 919 1580 / 3512 1454 GB	838 / 838 3146 / 3146 3035 GB	898 / 1664 1438 / 3146 7230 GB				2478 / 2937 6468 / 6927 42749 GB													4963 / 6358 12632 / 16731 54468 GB
CMCC-CM2-HR4													4 / 0 404 / 0 11 GB			4 / 0 268 / 0 109 GB	7 / 0 1821 / 0 122 GB						15 / 0 2493 / 0 242 GB
CMCC-CM2-VHR4													4 / 0 3005 / 0 1497 GB			8 / 0 5461 / 0 3733 GB	15 / 0 7877 / 0 1694 GB						27 / 0 16343 / 0 6924 GB
CNRM-CM6-1				195 / 389 274 / 637 1027 GB	1825 / 1825 2090 / 2090 2777 GB	280 / 500 1176 / 2508 4402 GB				4083 / 4083 16844 / 16844 51926 GB	306 / 306 979 / 979 5333 GB			4 / 0 16 / 0 14 GB		15 / 2 110 / 26 174 GB			282 / 1048 298 / 1211 275 GB	566 / 1036 626 / 1198 529 GB	637 / 1245 675 / 1410 677 GB	1261 / 1261 2537 / 2537 6722 GB	9454 / 11695 25625 / 29440 73856 GB
CNRM-CM6-1-HR																3 / 0 12 / 0 10 GB	1 / 0 1 / 0 1 GB						4 / 0 13 / 0 11 GB
CNRM-ESM2-1	353 / 394 470 / 550 966 GB	303 / 330 430 / 484 1005 GB		1029 / 1956 1319 / 3031 3225 GB	1457 / 1459 2340 / 2346 5839 GB	287 / 564 1166 / 2679 4253 GB	609 / 609 1106 / 1106 2890 GB	555 / 555 2214 / 2214 7275 GB	279 / 279 327 / 327 273 GB	2951 / 2951 8228 / 8228 24002 GB	576 / 576 2928 / 2928 7248 GB	273 / 273 322 / 322 272 GB							83 / 1695 84 / 2348 91 GB	528 / 1737 549 / 2038 676 GB	1091 / 2028 1192 / 2352 1900 GB	1899 / 1899 3321 / 3321 8375 GB	12273 / 17305 25996 / 34274 68290 GB
E3SM-1-0											46 / 46 46 / 46 36 GB												46 / 46 46 / 46 36 GB
[illegible]										761 / 1284						95 / 0			100 / 145	141 / 145	143 / 145	230 / 230	1470 / 1949
				379 GB	898 GB	807 GB				3762 GB	2249 GB												8095 GB
UKESM1-0-LL				735 / 993 1038 / 2297 1573 GB	430 / 430 1016 / 1016 1403 GB	169 / 302 187 / 396 257 GB				3381 / 3381 8890 / 8891 12752 GB	356 / 356 3879 / 3879 4671 GB								65 / 934 69 / 1985 25 GB	529 / 994 625 / 2130 308 GB	3 / 845 3 / 1805 0 GB	780 / 780 1640 / 1640 583 GB	6448 / 9015 17347 / 24039 21572 GB
43 Models	773 / 951 1624 / 2081 1984 GB	733 / 887 1584 / 2015 2000 GB	1102 / 1462 9027 / 11028 7177 GB	6536 / 10197 46873 / 68435 23241 GB	19402 / 19477 80080 / 80267 89546 GB	7842 / 12394 63076 / 492850 84162 GB	4674 / 4697 16288 / 16360 17230 GB	1138 / 1138 8613 / 8634 13612 GB	279 / 279 327 / 327 273 GB	61053 / 79417 351970 / 515967 437505 GB	7987 / 8463 110723 / 114555 224345 GB	667 / 667 717 / 717 960 GB	90 / 0 10436 / 0 2948 GB	33 / 0 1096 / 0 752 GB	17 / 0 559 / 0 475 GB	480 / 13 61124 / 901 23734 GB	410 / 0 38945 / 0 10756 GB	12 / 0 1086 / 0 567 GB	2124 / 11650 2700 / 47927 1354 GB	5285 / 12191 14548 / 47765 4921 GB	7250 / 15750 22024 / 51223 8713 GB	13533 / 13731 78413 / 79012 53702 GB	141420 / 193364 921833 / 1540064 1009957 GB

CMIP5 vs. CMIP6 Models

Preliminary ILAMB Analysis indicates:

- For most variables and models, the CMIP6 land models (right) perform better overall than the CMIP5 land models (left)
- The CMIP5 and CMIP6 multi-model means perform better than any single model in their respective collections
- The multi-model mean of the CMIP6 models outperforms all models, although for a few variables, an individual model may perform better

https://www.ilamb.org/CMIP5v6/historical/



(Hoffman *et al.*, in prep.)

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For more information...

- **Reducing Uncertainties in Biogeochemical Interactions through Synthesis and Computation (RUBISCO) Scientific Focus Area**
  https://www.bgc-feedbacks.org/

- **DOE CMIP6 Analysis Hackathon**
  Slack: https://doe-cmip6.slack.com/
  GitHub: https://github.com/wilbertw/RGMA-CMIP6-Analysis-Scripts

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