Introducing the
Coordinated Model Evaluation Capabilities (CMEC)

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CMEC
Coordinated Model Evaluation Capabilities

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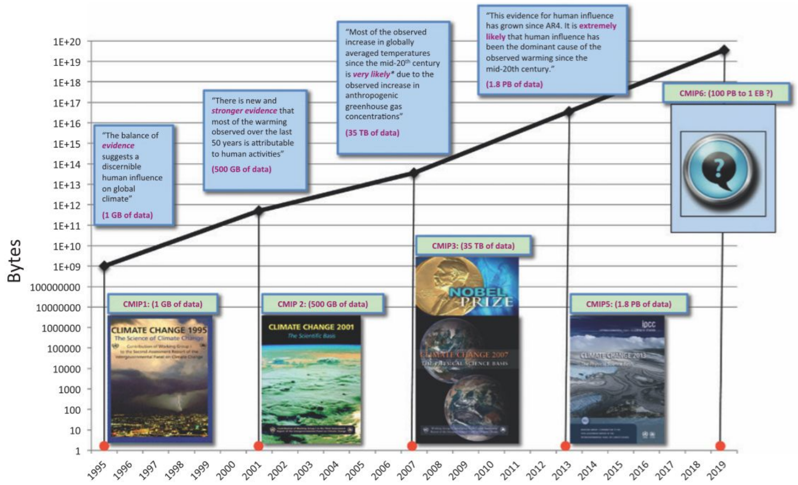
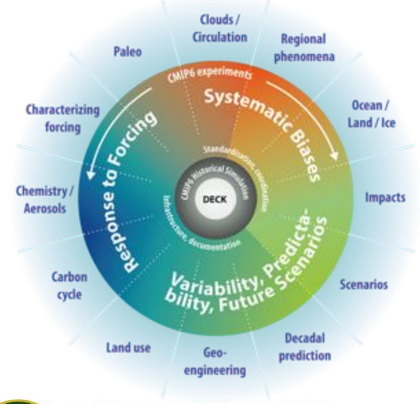
Motivation

- The rapid growth in number, scale and complexity of simulations necessitates efficient analysis
- Established model evaluation methods need to be routinely applied and results readily accessible
- Community-based building blocks are a viable mechanism to accomplish this

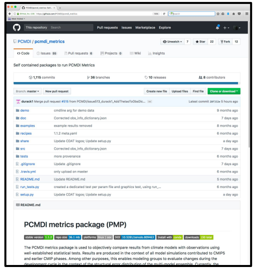


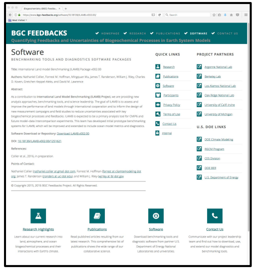


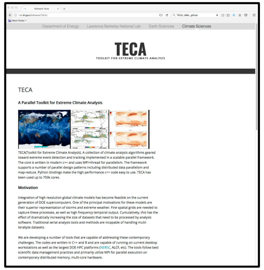
DOE is developing several model evaluation packages

<u>Within RGCM:</u>

- PCMDI Metrics Package (PMP)
- The International Land Model Benchmarking (ILAMB) Package
- The International Ocean Model Benchmarking (IOMB) Package
- Parallel Toolkit for Extreme Climate Analysis (TECA)







- These are highly complementary, and collectively capture an extensive suite of model evaluation characteristics
- They will help accelerate research for CMIP6 synthesis papers

CMEC is an attempt to coordinate the development of these efforts and provide results via a common portal

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Establishing protocols for coordinating model evaluation capabilities, starting within RGCM

Akin to the grass roots development of CMIP data conventions, CMEC strives to coordinate analysis capabilities via:

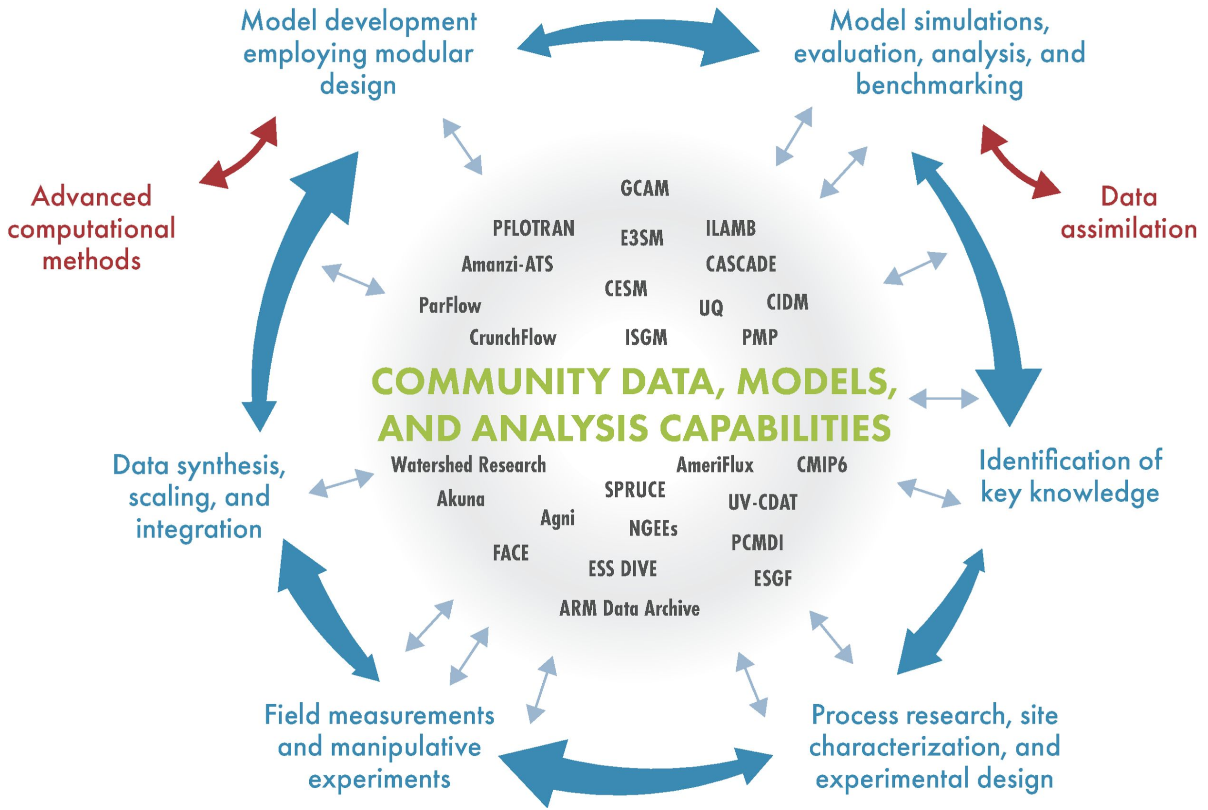
- Protocols for input data and interoperability
- Strategies for software accessibility and documentation
- Provenance guidelines to ensure reproducibility

Like the establishment of CMIP, this is going to be a process

What can we expect from CMEC?

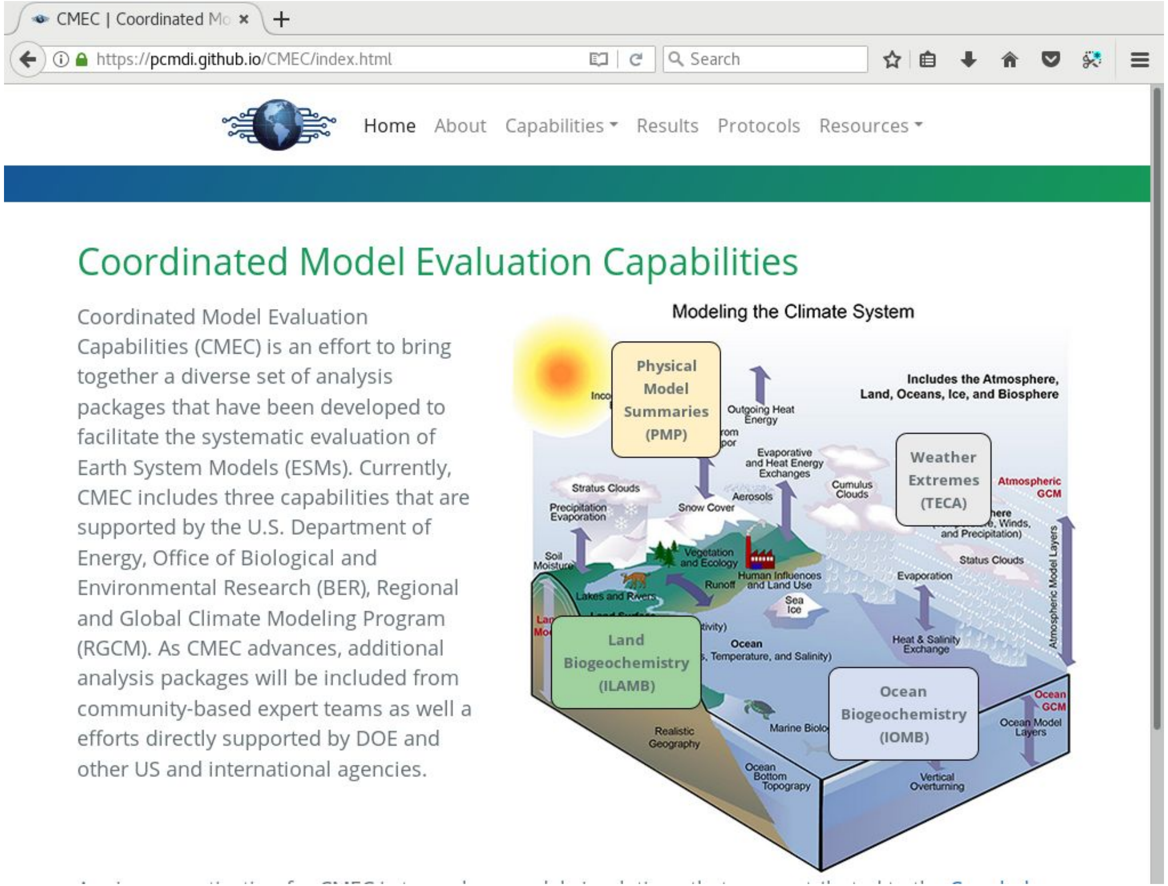
- More directly contribute to model development (via useful quick feedback)
- Raise-the-bar on model evaluation
- Advance science more efficiently and make model evaluation results more accessible
- Facilitate national assessments, the IPCC process, etc.

CMEC can facilitate synergies within DOE



DOE's Model-Data-Experiment Enterprise

CMEC Website



Website is visible via GitHub but not yet indexed by search engines

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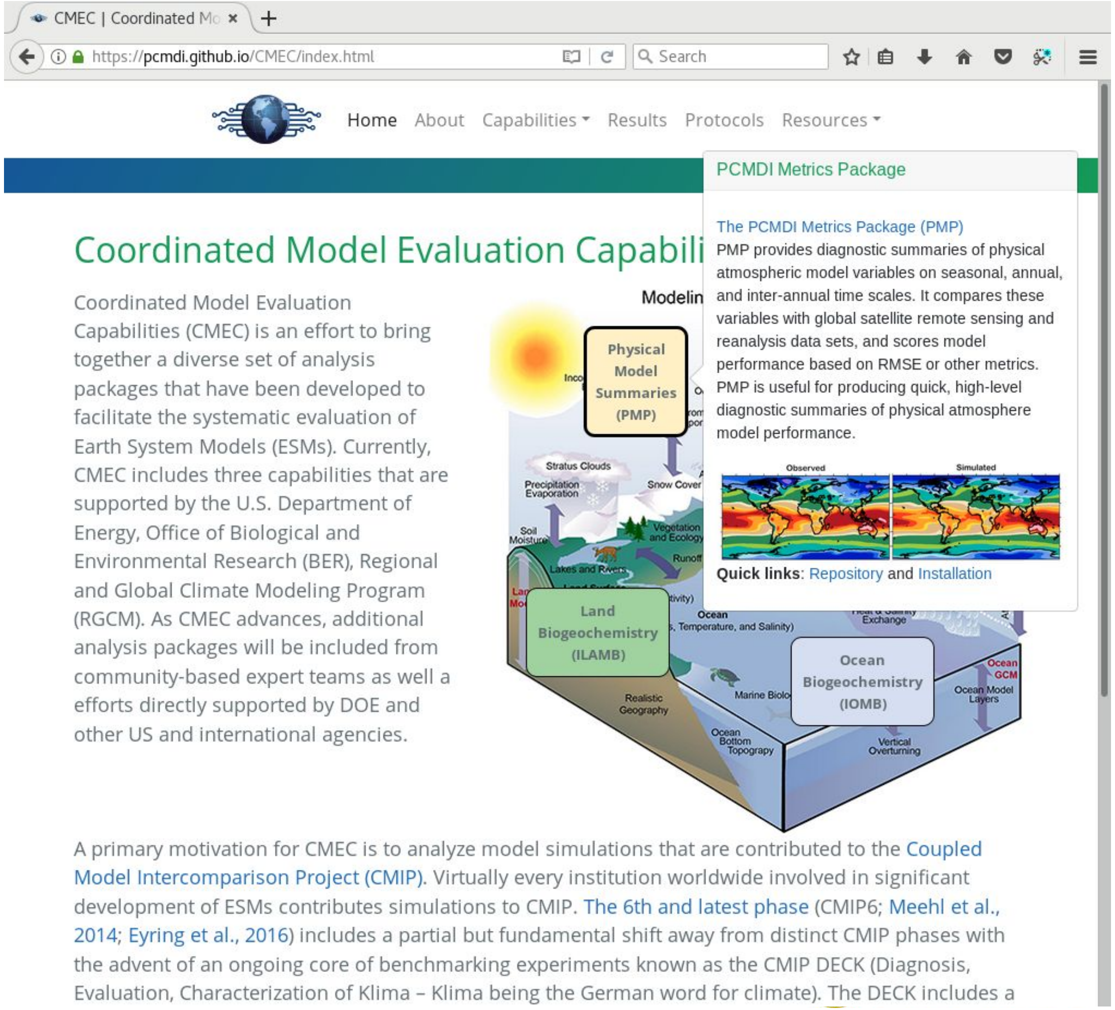
Questions we will address in this presentation

- Who are the targeted users?
- What is the potential value for DOE?
- What other activities within DOE can contribute to CMEC?
- What impact can it have on the general community and Earth system science?
- What do we see as the future of CMEC?

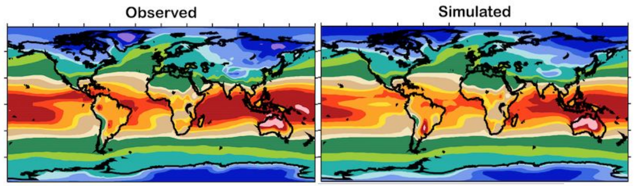
PMP

The PCMDI Metrics Package (PMP) provides a diverse suite of relatively robust high level summary statistics comparing models and observations across space & time scales



The PCMDI Metrics Package (PMP)

https://github.com/PCMDI/pcmdi_metrics



- Includes metrics and underlying diagnostics from:
    - PCMDI research
    - Collaborations with expert teams (e.g., CLIVAR ENSO group)

- Working with 5 modeling groups (E3SM, GFDL, NCAR, IPSL, ACCESS)

- Leveraging DOE supported python based tools

- Developing end-to-end provenance to ensure reproducibility

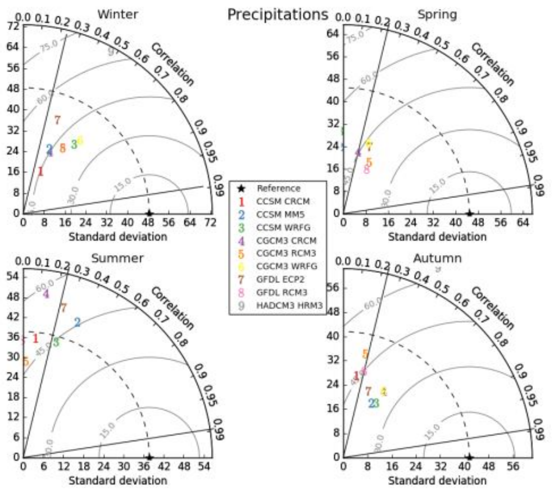
The PCMDI Metrics Package (v1.1.x)

Prototyped on experience with climatological summaries

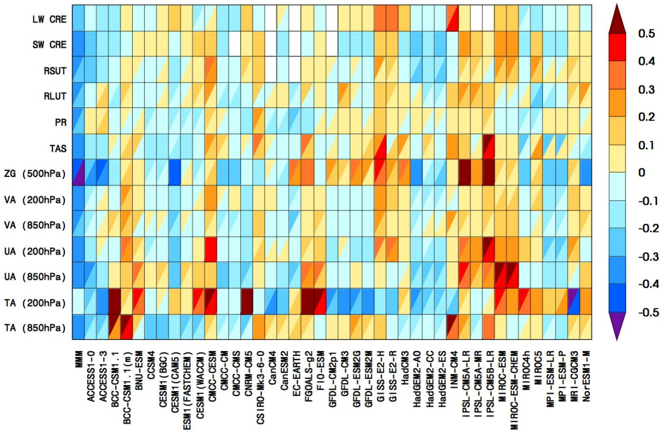
PCMDI metrics used in the IPCC TAR, AR4 and AR5 to:

1) Gauge model improvements over time
2) Identify the strengths and weaknesses of different models

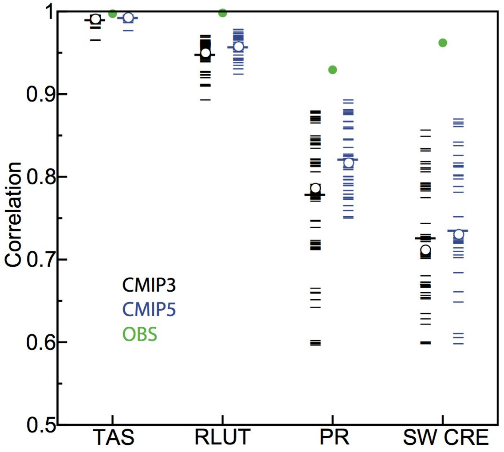
AR4 Chapter 8



AR5 Chapter 9



AR5 Chapter 9



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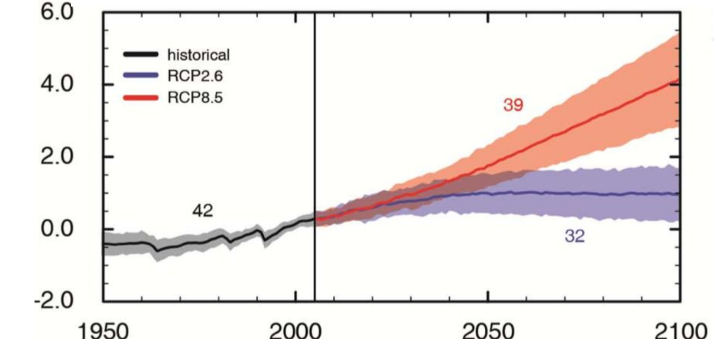
The quest for moving beyond “One Model One Vote”

- For the first time in the IPCC, the AR5 CMIP5 multi-model projections involved weighting based on metrics of sea-ice extent (mean state and trend)

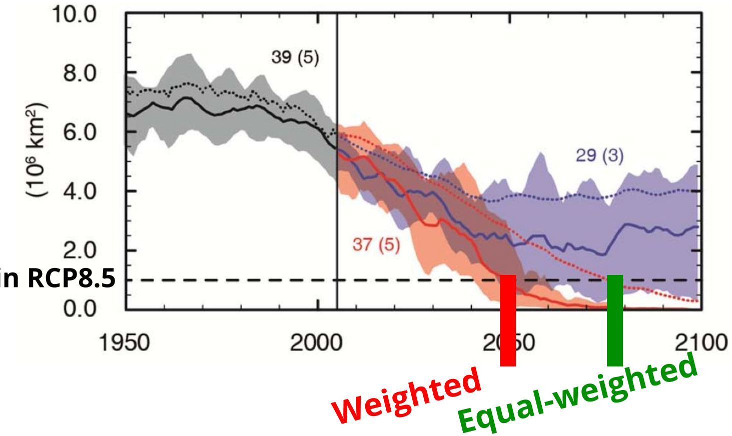
- A weighted MME results yields an “ice free” ($<10^6$ km^2) September Arctic nearly 3 decades earlier

Figure AR5 SPM.7

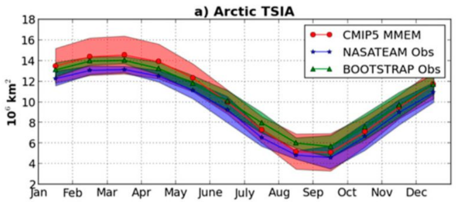
Global Average Surface Temperature



N. Hemisphere September sea ice extent



Projected year of “ice-free” Arctic in RCP8.5

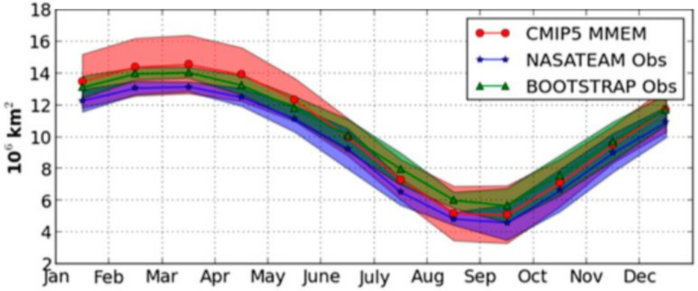


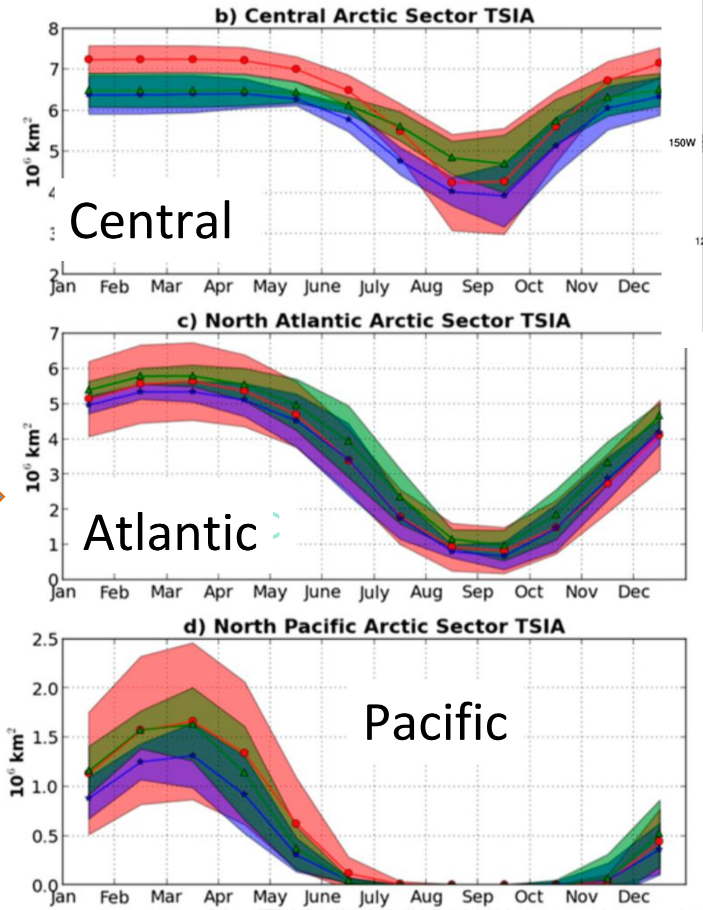
Metrics based on TOTAL Arctic

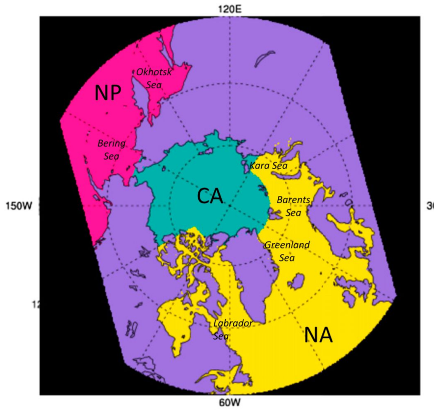
Sector Scale Sea Ice

CMIP5 MME compared to 2 satellite estimates (1979-2005)

Total Arctic





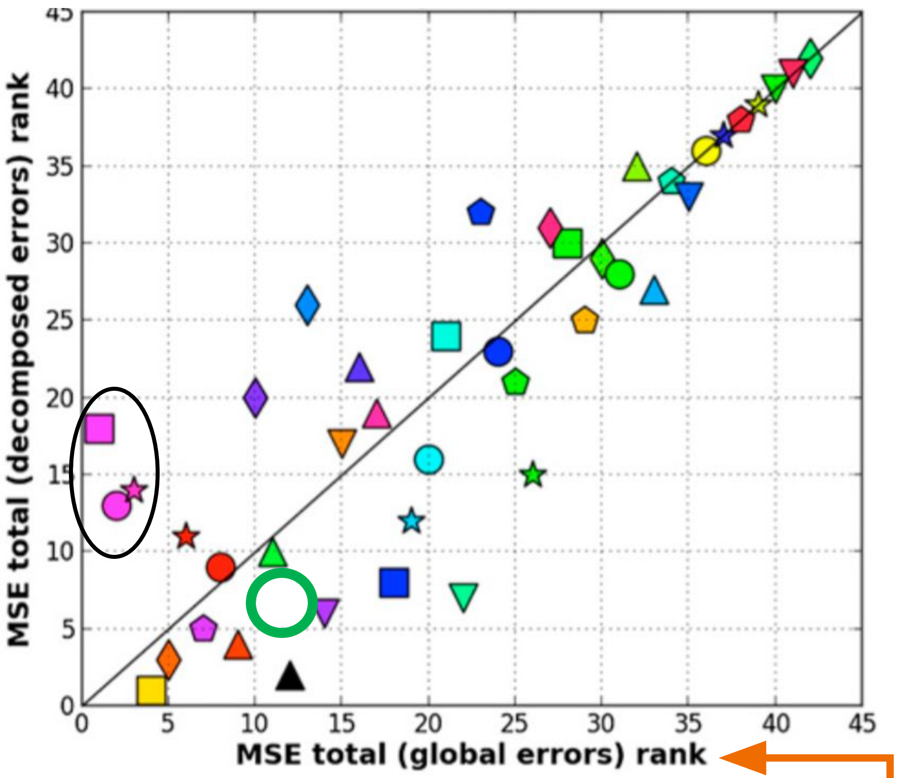


Ivanova et al., J. Climate, 2016

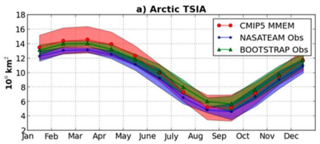
Native grid sector scale combining "ice area" errors of N. Atl, N. Pac and central Arctic

Sea ice metrics: Exposing compensating errors

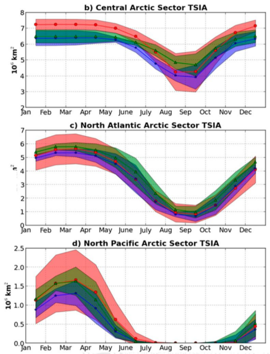
CMIP5 Ranking of Arctic Ice Annual Cycle



Total Arctic



versus



Central Arctic

N. Atlantic

N. Pacific

- Comparison “global” vs “sector scale” total ice errors

- <u>Substantial error compensation</u>, in some “better” performing models

Traditional method

Ivanova et al., J. Climate, 2016

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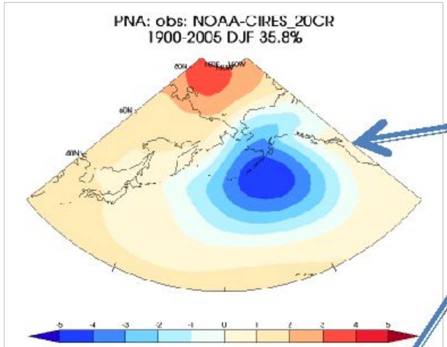
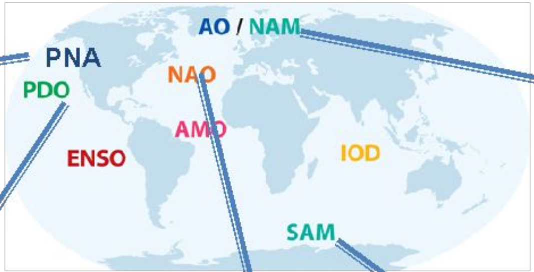
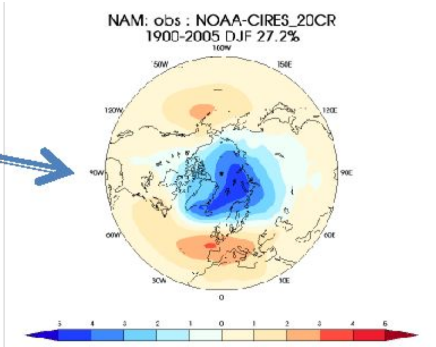
Extra-tropical Modes of Variability
Generally defined by EOF leading mode in observations

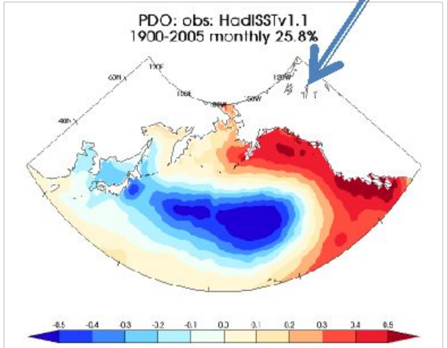


PNA: Pacific North American Pattern
(20CR, SLP)

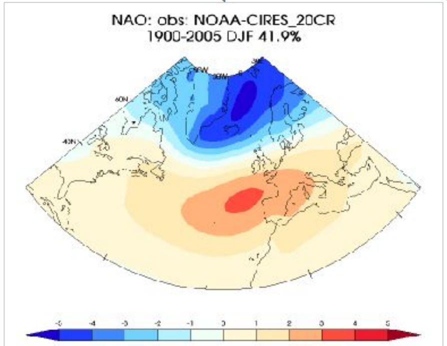




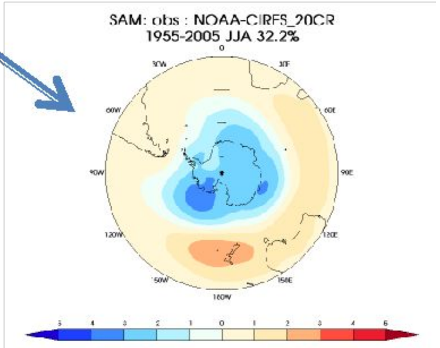
NAM: Northern Annular Mode
(20CR, SLP)



PDO: Pacific Decadal Oscillation
(HadISSTv1.0, SST)

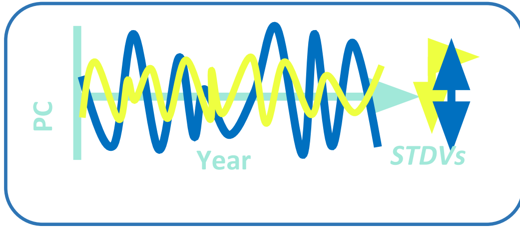


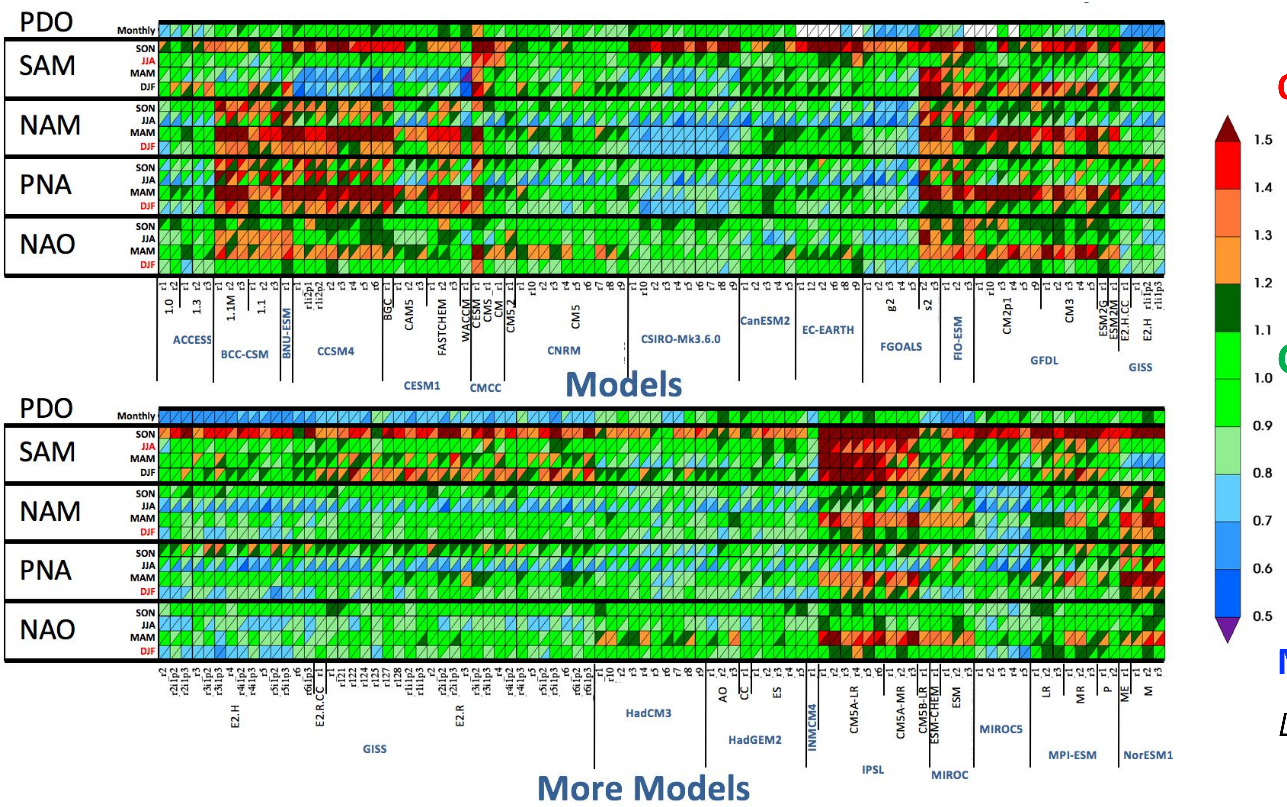
NAO: Northern Atlantic Oscillation
(20CR, SLP)



SAM: Southern Annular Mode
(20CR, SLP)

Simulated/reference amplitude ratios CMIP5 historical simulations (1900-2005)

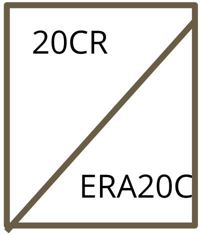




Overestimate

Good

Muted



Lee et al., 2017, in review

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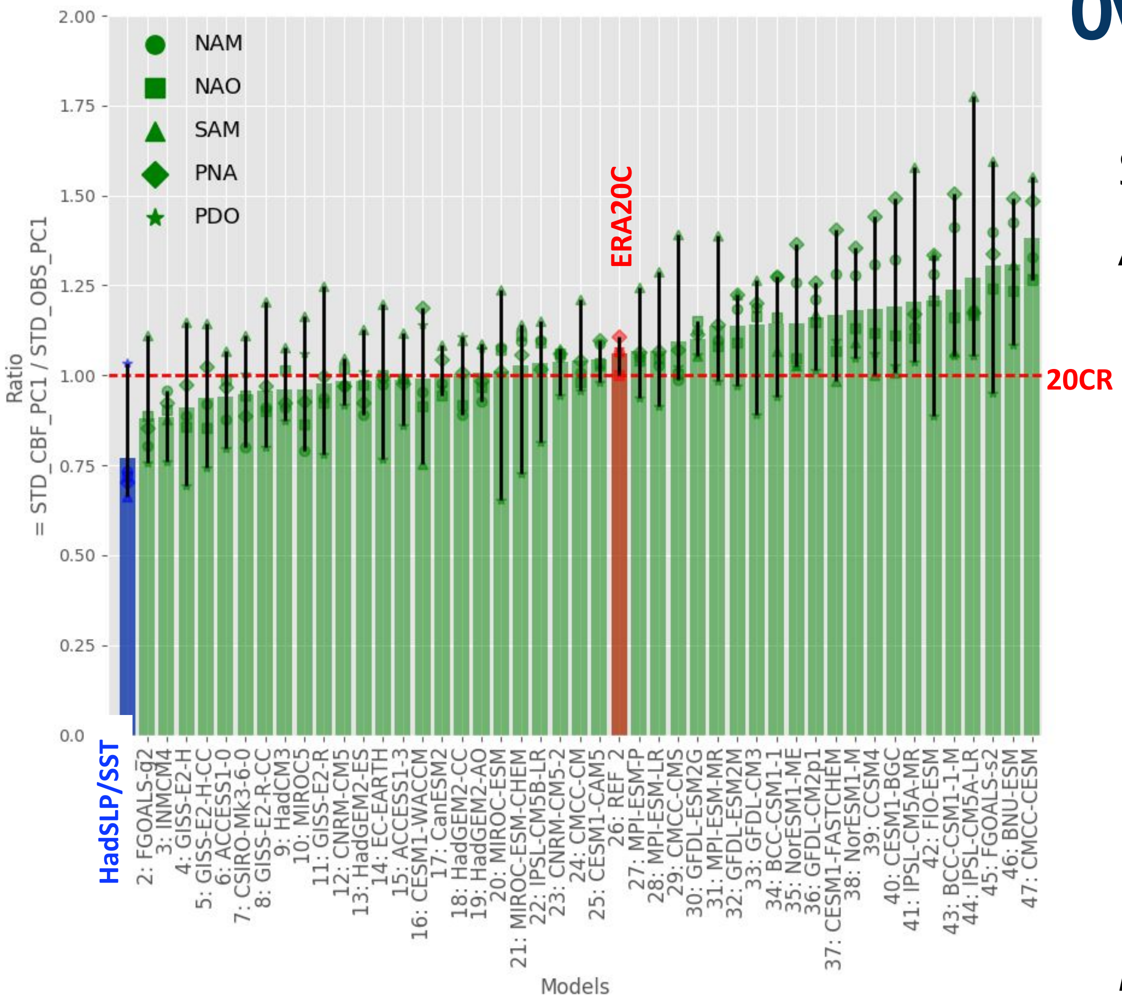
Interactive access to underlying diagnostics available on CMEC website

Overall Amplitude Behavior



Simulated/Obs amplitude ratios

Averaging realizations, seasons

Bar height: AVG across modes

Error compensation (across modes)

Lee et al., 2017, in review

The PCMDI Metrics Package (PMP)

Implemented

- Orthogonal decompositions of climatological physical characteristics at regional to global scales
- Extra-tropical modes of variability
- ENSO (collaboration with CLIVAR panel)
- High frequency characteristics of simulated precipitation
- Regional monsoon precipitation indices
- Sector scale sea-ice

In Progress

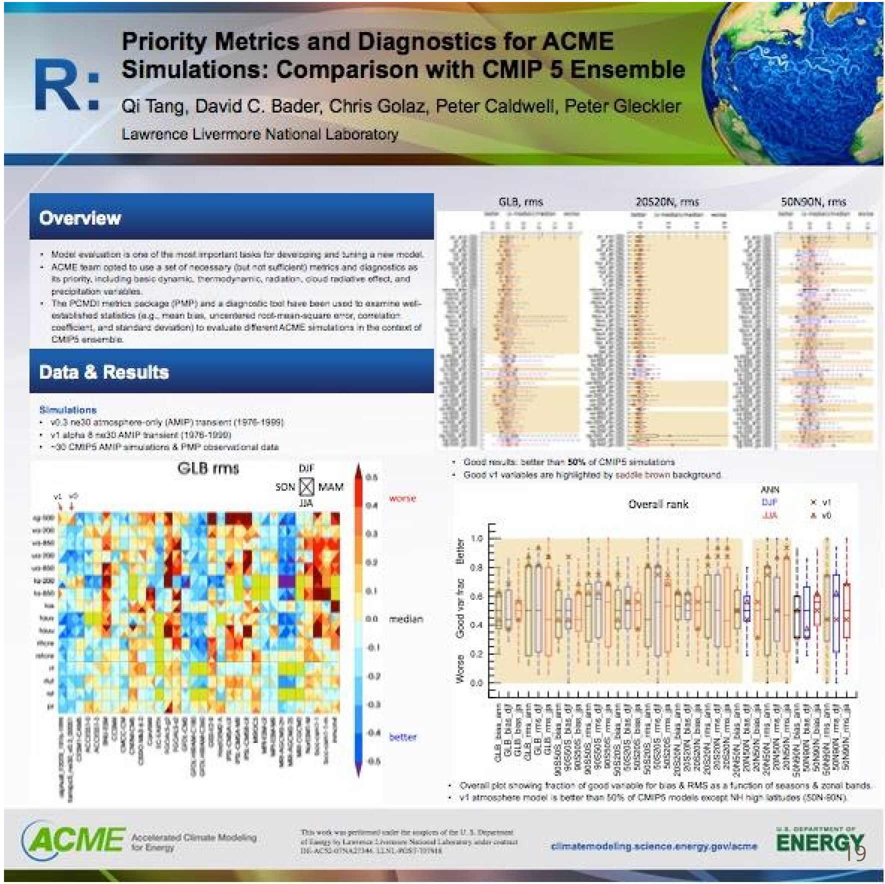
- Cloud properties (collaboration with S. Klein’s group)
- Extensive ocean T&S (ARGO) metrics based on PCMDI research
- Tropical waves
- Working with expert teams to establish targeted benchmarks (e.g., WCRP precipitation group, ocean panel)

CMEC

PMP highlights

PCMDI Metrics Package

- Will deliver new metrics to E3SM and other modeling groups
- PMP high level summaries for CMIP6 will be prominent
- Leveraging six generations of MIPs to track model improvements since 1990
- An increasingly diverse set of metrics will further expose compensating errors
- Poised for next generation: Integration with ESGF and server side analysis



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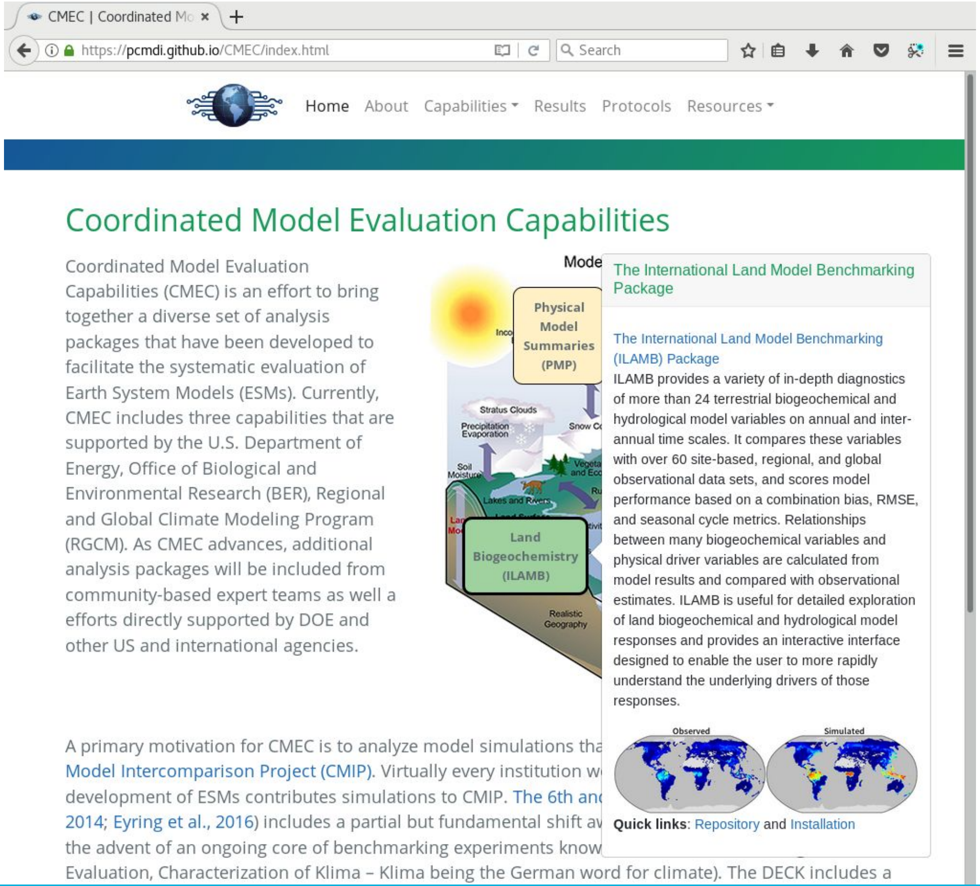
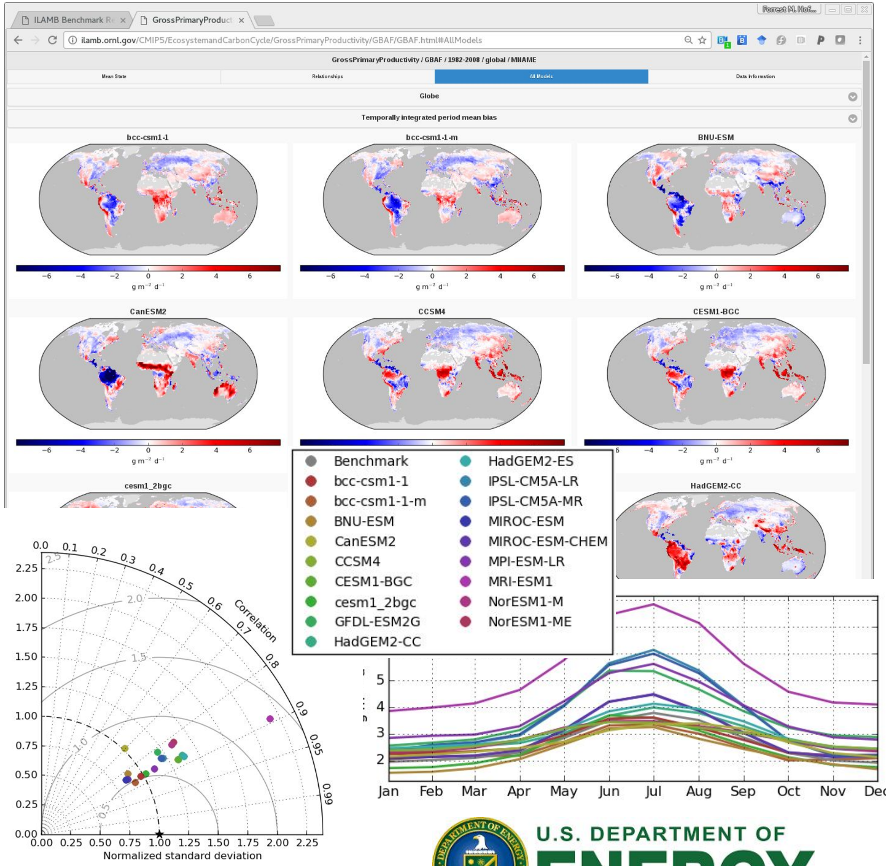
International Land Model Benchmarking (ILAMB) Package





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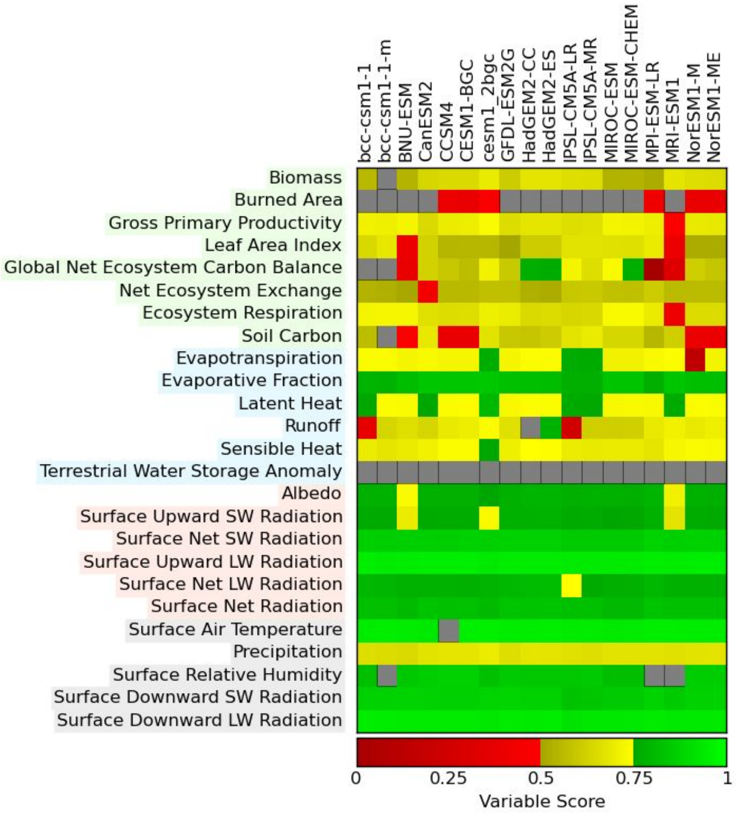
International Land Model Benchmarking (ILAMB) Package

- Provides systematic assessment of land model results compared with observations
- Scores model performance across a wide range of independent benchmark data sets
- Includes comparison of functional relationships (variable-to-variable comparisons)
- Written in Python and runs in parallel
- Produced from an international community coordination effort for designing metrics
- Supported primarily by RUBISCO SFA with support for metrics from E3SM and new observational data from NGEE Arctic & Tropics



International Land Model Benchmarking (ILAMB) Package

- We invested effort in providing a rich hierarchical user interface
- The top level overview provides “portrait plots” of absolute and relative model scores
- Scores are aggregated from multiple data sets and metrics for each variable

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ILAMB Package Features

- Currently integrates analysis of 25 variables in 4 categories from ~60 datasets
  - aboveground live biomass, burned area, carbon dioxide, gross primary production, leaf area index, global net ecosystem carbon balance, net ecosystem exchange, ecosystem respiration, soil carbon
  - evapotranspiration, latent heat, sensible heat, runoff, evaporative fraction, terrestrial water storage anomaly
  - albedo, surface upward SW + LW radiation, surface net SW + LW radiation, surface net radiation
  - surface air temperature, precipitation, surface relative humidity, surface downward SW +LW radiation
- Graphics and scoring system
  - plots and scores model performance for annual mean, bias, relative bias, RMSE, seasonal cycle phase, spatial distribution, interannual variability, variable-to-variable comparisons
  - includes global maps, time series plots averaged over specific regions, individual measurement sites, functional relationship plots, capability to zoom in on specific regions
- Open Source (https://www.ilamb.org/)
  - ILAMBv2.2 is available at https://www.bgc-feedbacks.org/software/

CMEC

ILAMB Package Results Table

ILAMB Benchmark Results

Mean State | Relationship | Results Table

Biomass	0.59	0.64	0.66	0.65	0.67	0.67
Burned Area	0.35	0.47	0.55	0.35	0.48	0.55
Gross Primary Productivity	0.68	0.73	0.75	0.71	0.74	0.74
Fluxnet (37.5%)	0.68	0.71	0.73	0.70	0.73	0.72
GBAF (62.5%)	0.68	0.74	0.76	0.72	0.74	0.75
Leaf Area Index	0.50	0.55	0.63	0.57	0.60	0.68
Global Net Ecosystem Carbon Balance	0.56	0.70	0.76	0.71	0.64	0.86
Net Ecosystem Exchange	0.56	0.57	0.60	0.56	0.57	0.60
Ecosystem Respiration	0.63	0.69	0.72	0.67	0.73	0.73
Soil Carbon	0.46	0.62	0.32	0.40	0.62	0.44
Ecosystem and Carbon Cycle Summary	0.55	0.63	0.62	0.58	0.63	0.66
Evapotranspiration	0.73	0.76	0.76	0.76	0.79	0.79
Evaporative Fraction	0.81	0.82	0.80	0.81	0.83	0.82
Latent Heat	0.76	0.79	0.79	0.78	0.81	0.83
Runoff	0.69	0.75	0.69	0.81	0.81	0.78
Sensible Heat	0.73	0.74	0.72	0.75	0.77	0.76
Terrestrial Water Storage Anomaly	0.49	0.49	0.48	0.48	0.48	0.47
Hydrology Cycle Summary	0.70	0.73	0.71	0.73	0.74	0.74
Albedo	0.73	0.73	0.74	0.73	0.73	0.74
Surface Upward SW Radiation	0.74	0.73	0.73	0.75	0.74	0.74
Surface Net SW Radiation	0.78	0.78	0.78	0.79	0.79	0.79
Surface Upward LW Radiation	0.84	0.84	0.84	0.84	0.84	0.84
Surface Net LW Radiation	0.72	0.71	0.70	0.78	0.77	0.76
Surface Net Radiation	0.73	0.73	0.73	0.75	0.75	0.74

- Results Table shows scores for each model (columns) by variable (rows)
- Each variable is a “pull-down” for multiple data sets (see GPP for Fluxnet and GBAF)
- Clicking on the data set opens a new browser tab with tabular and graphical diagnostics

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ILAMB Package Results Table

ilamb.ornl.gov/CMIP5/EcosystemandCarbonCycle/GrossPrimaryProductivity/GBAF/GBAF.html

GrossPrimaryProductivity / GBAF / 1982-2008 / global / cesm1_2bgc

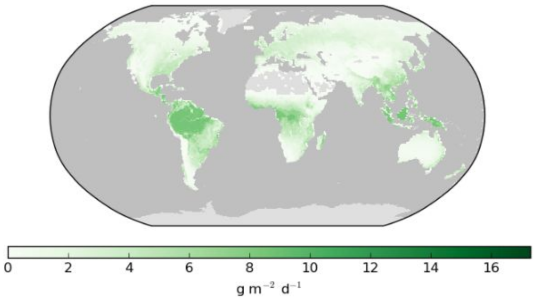
Mean State | Relationships | All Models | Data Information

Globe

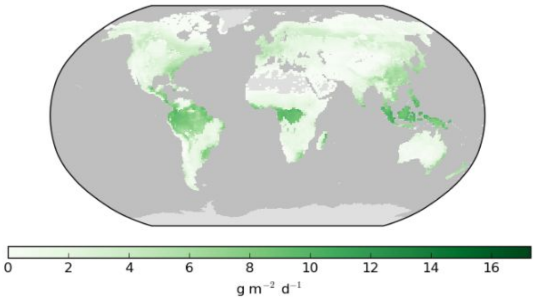
Model	Data	Period Mean [Pg yr-1]	Bias [Pg yr-1]	RMSE [Pg yr-1]	Phase Shift [months]	Bias Score [1]	RMSE Score [1]	Seasonal Cycle Score [1]	Spatial Distribution Score [1]	Overall Score [1]
Benchmark	[-]	113.064								
bcc-csm1-1	[-]	115.724	7.429	78.476	1.204	0.724	0.596	0.805	0.931	0.73
bcc-csm1-1-m	[-]	107.094	-4.224	83.538	1.277	0.719	0.577	0.803	0.93	0.721
BNU-ESM	[-]	97.02	-11.485	70.83	1.189	0.71	0.638	0.809	0.9	0.739
CanESM2	[-]	114.499	5.115	92.059	1.91	0.64	0.569	0.676	0.848	0.66
CCSM4	[-]	123.702	13.958	75.568	1.326	0.686	0.614	0.758	0.869	0.708
CESM1-BGC	[-]	123.332	13.543	74.958	1.316	0.689	0.616	0.765	0.87	0.711
cesm1_2bgc	[-]	105.976	-3.626	69.608	1.384	0.718	0.649	0.766	0.933	0.743
GFDL-ESM2G	[-]	153.167	49.933	129.535	1.405	0.659	0.495	0.729	0.878	0.651
HadGEM2-CC	[-]	125.891	18.303	92.441	1.17	0.675	0.548	0.783	0.848	0.681
HadGEM2-ES	[-]	130.407	23.084	94.021	1.16	0.676	0.544	0.787	0.847	0.68
IPSL-CM5A-LR	[-]	156.454	47.855	111.502	1.243	0.63	0.528	0.766	0.889	0.668
IPSL-CM5A-MR	[-]	157.372	45.797	113.639	1.241	0.633	0.524	0.762	0.892	0.667
MIROC-ESM	[-]	117.498	12.456	77.895	1.316	0.732	0.634	0.753	0.9	0.731
MIROC-ESM-CHEM	[-]	118.063	13.02	78.062	1.336	0.732	0.634	0.747	0.904	0.73
MPI-ESM-LR	[-]	163.389	51.05	97.411	1.373	0.677	0.593	0.705	0.923	0.698
MRI-ESM1	[-]	229.614	125.717	180.282	1.305	0.411	0.345	0.788	0.547	0.487
NorESM1-M	[-]	124.258	13.645	78.707	1.319	0.66	0.597	0.767	0.838	0.692
NorESM1-ME	[-]	125.106	14.623	79.898	1.331	0.654	0.592	0.769	0.827	0.687

Temporally integrated period mean

BENCHMARK MEAN



MODEL MEAN

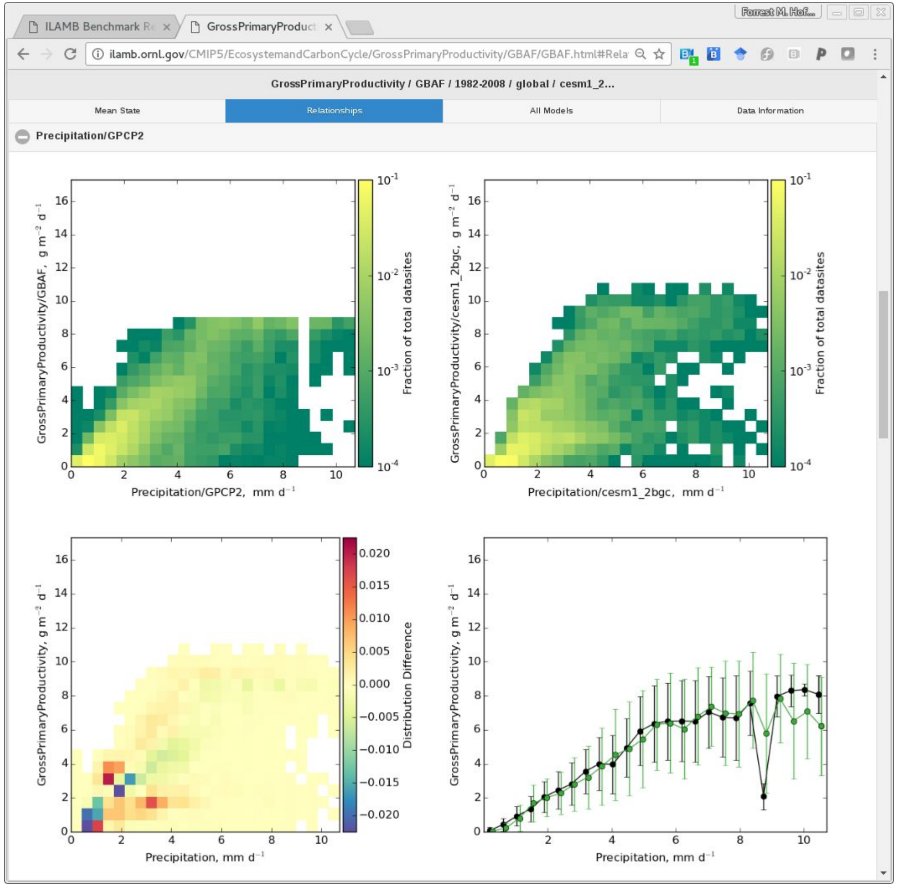


MAPPED MODEL MEAN

BIAS

- Models can be selected individually and diagnostics update
- Separate statistics and figures are produced for pre-defined regions
- Relationships tab contains variable-to-variable comparisons
- Data provenance provided in Data Information tab

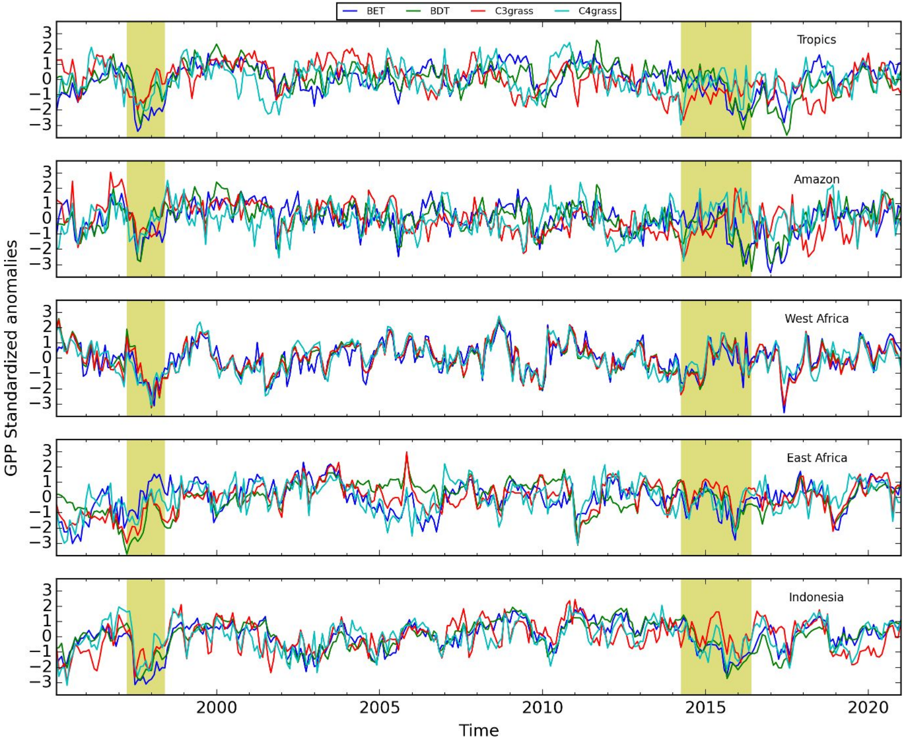
ILAMB Functional Relationships



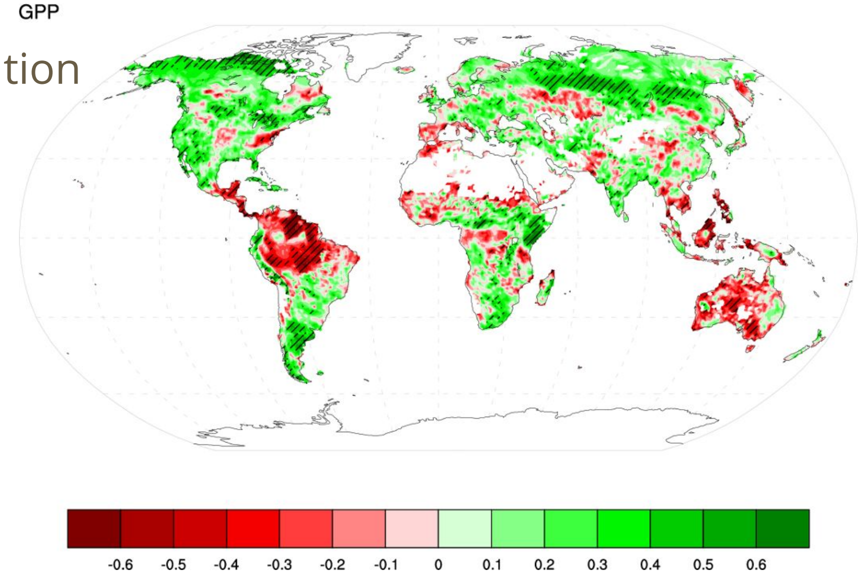
- Variable-to-variable comparisons provide a better way to understand model responses to forcing
- Shown here is GPP vs. Precipitation for a single model compared with observations
- Differences in distribution of points suggests regimes in which model errors are most significant
- Histogram-style line plots indicate if model exhibits overall relationships emerging from observational data

El Niño Modeling with E3SM for NGEE Tropics

Systematic evaluation of model results leads to creation of new phenomenon- and region-specific metrics

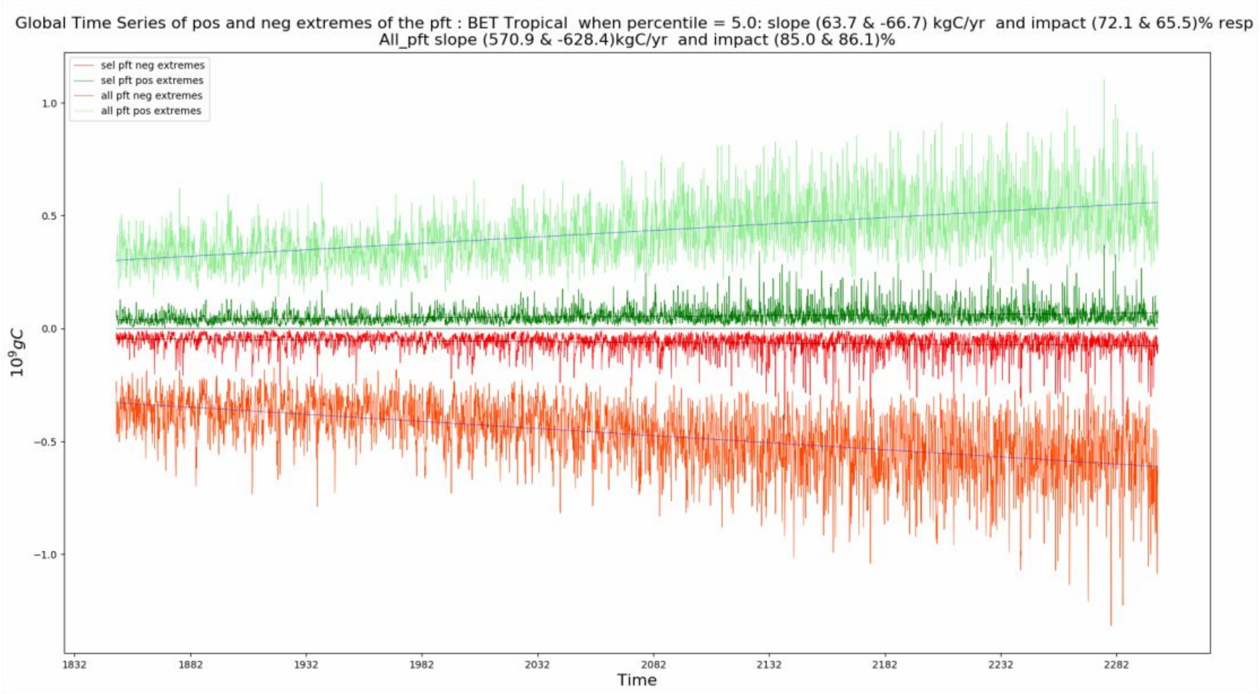


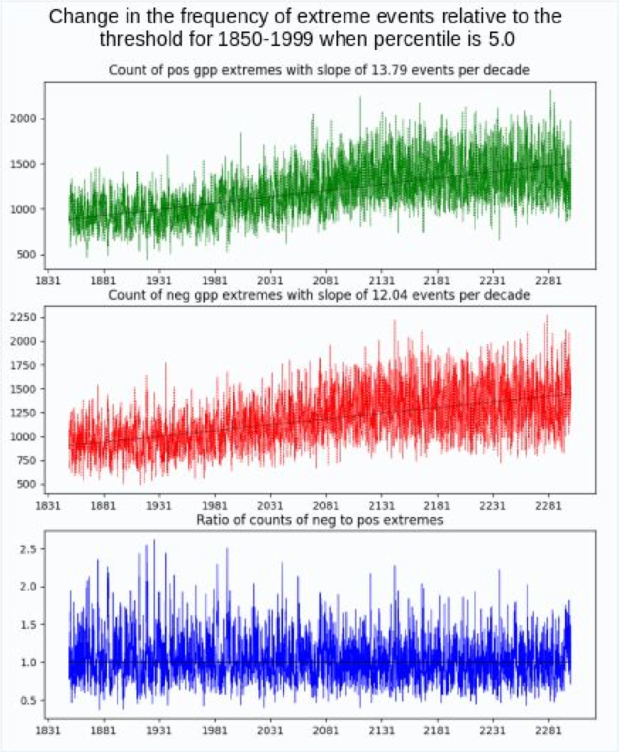
PFT-level tropical ecosystem responses to ENSO-induced drought (left).



Correlation of annual gross primary production with 5-month averages of sea surface temperatures over the Niño 3.4 region (November--February) during 1995--2016. The hatching indicates locations where the correlation is at a 90% confidence level or higher.

Spatio-Temporal Analysis of GPP Anomalies from Extreme Events





We removed annual and >decadal signals from GPP to extract anomalies and investigate projected changes in frequency and intensity

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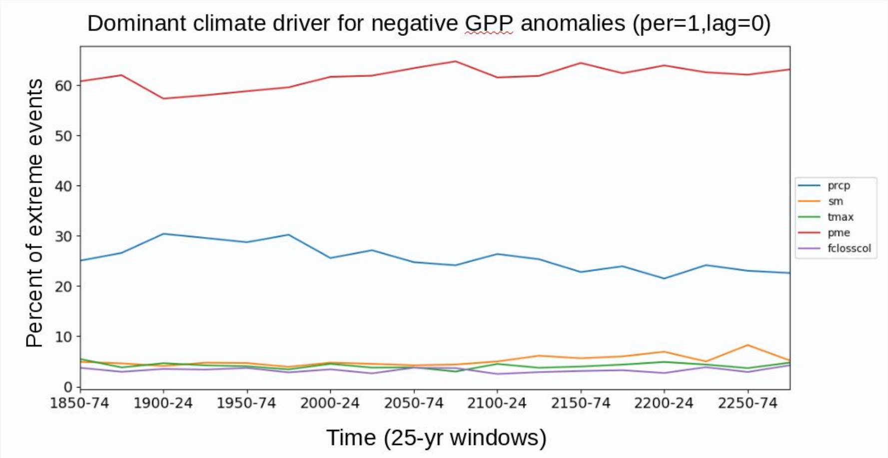
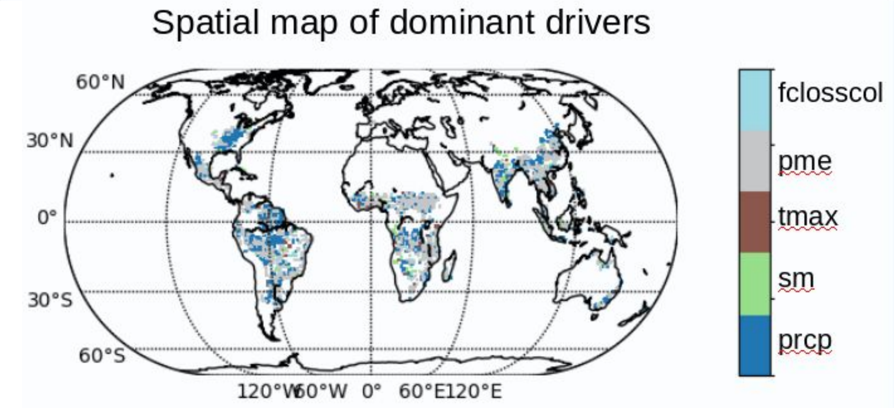
Attribution of Climate Drivers to GPP Anomalies





- Multi-linear regression of negative GPP anomalies with
  - Precipitation minus Evapotranspiration
  - Maximum daily temperature
  - Soil moisture to 1-m depth
  - Precipitation

  indicated dominant drivers of largest (1st percentile in 25 yr window) productivity losses (for $t_{lag} = 0$)
- Next step: Add time lags to attribute causes of largest extreme events
- Spectral analysis tool, new metrics will be added to ILAMB

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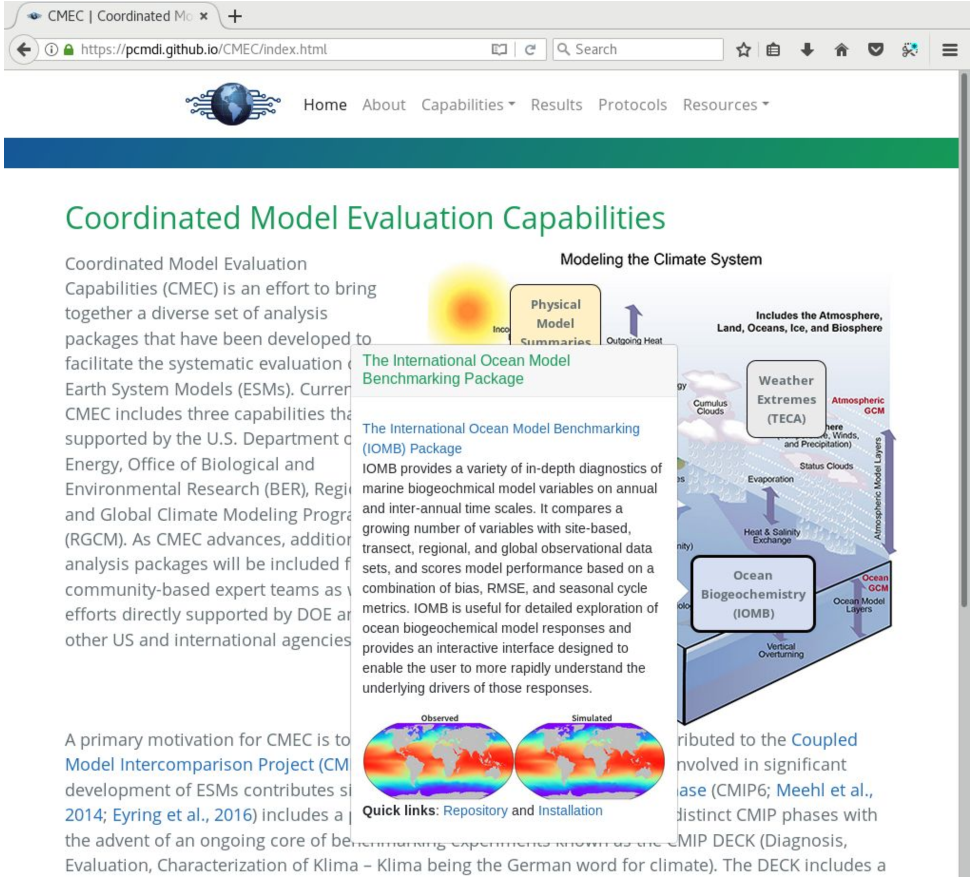
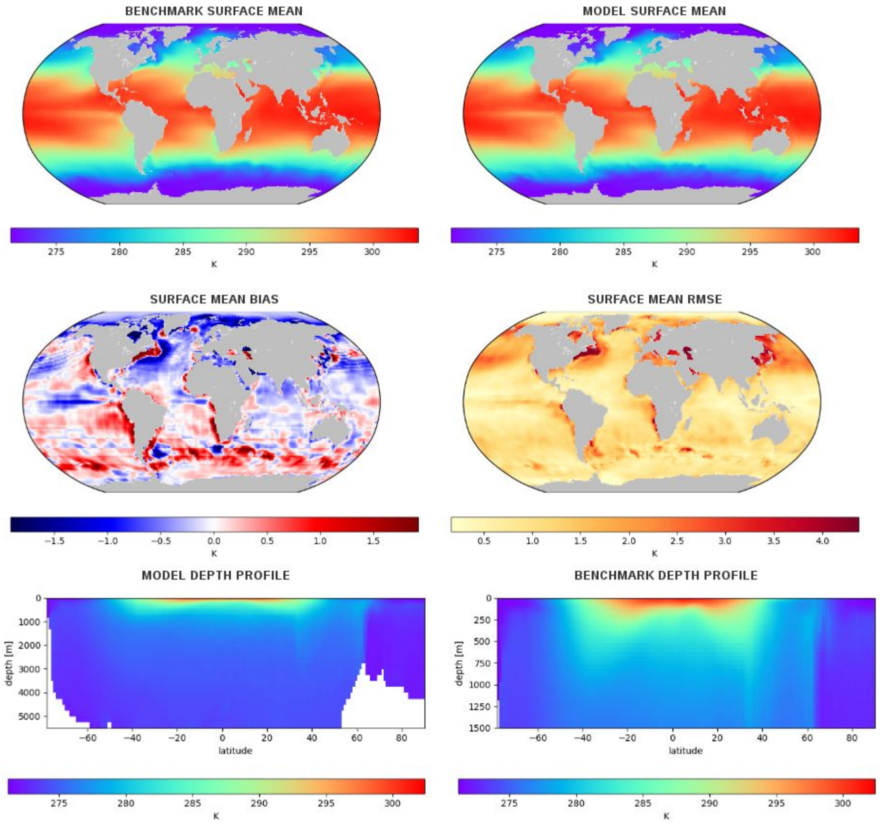
International Ocean Model Benchmarking (IOMB) Package



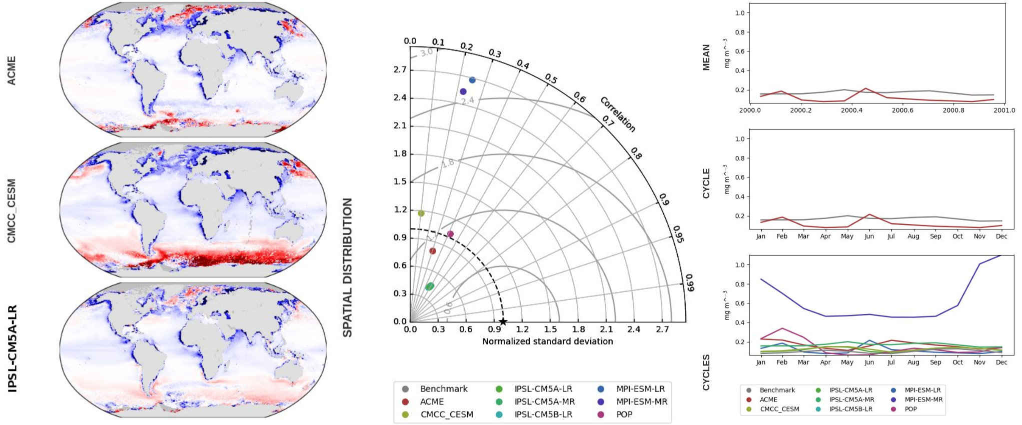


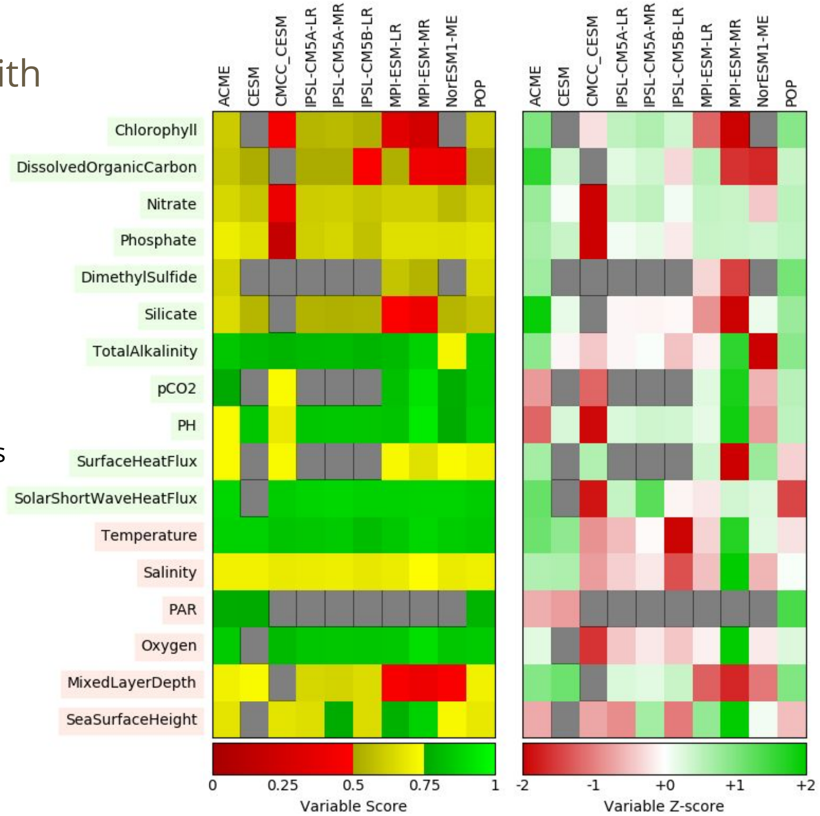
International Ocean Model Benchmarking (IOMB) Package

- Evaluates ocean biogeochemistry results compared with observations (global, regional points, and ship tracks)
- Scores model performance across a wide range of independent benchmark data
- Leverages ILAMB code base; also runs in parallel
- Will be released to the community soon

Chlorophyll / SeaWIFS

Bias | Spatial Distribution | Annual & Seasonal Cycles



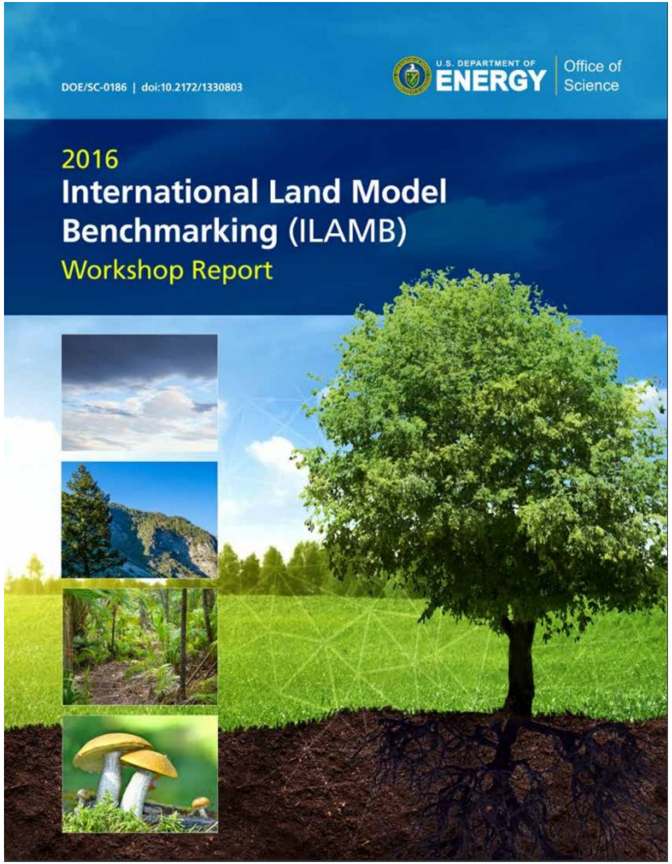


ILAMB and IOMB Target Uses

- ILAMB is designed for use by
  - Individual modelers/model developers - for verification
  - Modeling centers - to track model performance evolution
  - Model intercomparison experiments - for multi-model analysis

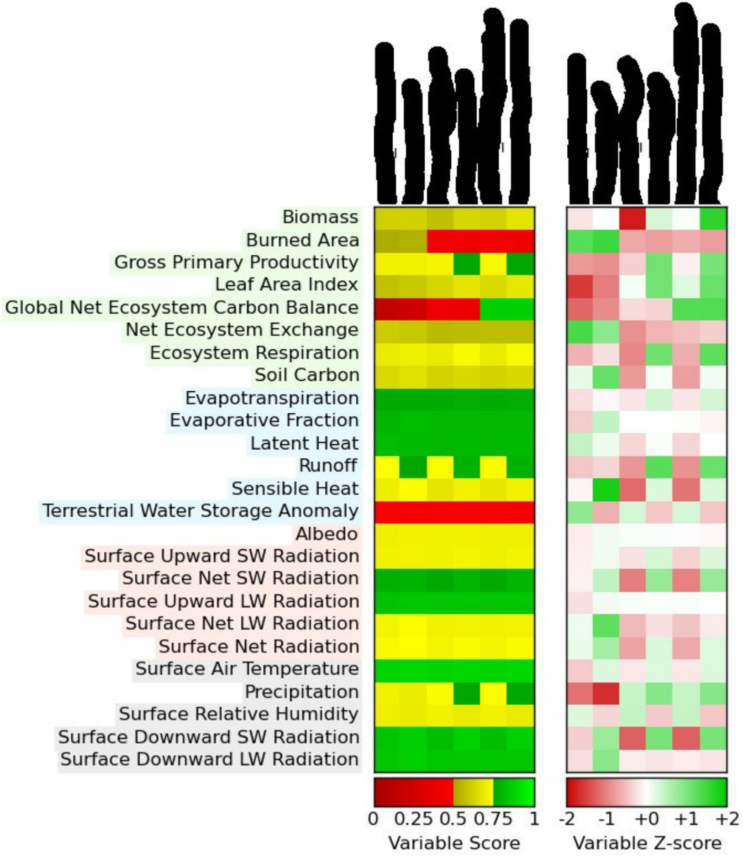
- ILAMB is being used & developed by the international land model community
  - DOE E3SM - Workflow and Land Model Intercomparison
  - NSF / DOE CESM at NCAR - Workflow (land and ocean)
  - University of New South Wales / PALS / modelevaluation.org - Analysis engine
  - CEH / JULES / EartH2Observe - Published analysis
  - NOAA GFDL - Adding it to their toolkit
  - NASA ABoVE / NOAA NSIDC - Permafrost metrics
  - University of Tokyo / GSWP3 - Runoff metrics and evaluation

- IOMB is being used & developed by E3SM & CESM so far



E3SM Land Model (ELM) Intercomparison

CMEC



Gross Primary Productivity / GBAF / 1982-2008

	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	[-]	118.810												
[redacted]	[-]	111.448	102.592	8.851	118.383	0.427	-0.037	1.573	1.244	0.727	0.648	0.812	0.862	0.739
[redacted]	[-]	105.181	97.013	8.162	118.383	0.427	-0.185	1.536	1.254	0.737	0.654	0.798	0.865	0.741
[redacted]	[-]	138.154	128.193	9.954	118.383	0.427	0.542	1.614	1.181	0.745	0.644	0.825	0.864	0.744
[redacted]	[-]	137.237	127.339	9.891	118.383	0.427	0.523	1.619	1.139	0.746	0.642	0.825	0.865	0.744
[redacted]	[-]	126.756	117.893	8.856	118.383	0.427	0.281	1.404	1.335	0.790	0.685	0.801	0.899	0.772
[redacted]	[-]	125.544	116.790	8.748	118.383	0.427	0.255	1.412	1.303	0.789	0.681	0.802	0.900	0.771

- An enhanced version of ILAMB is being used to assess multiple land biogeochemistry formulations in ELM
- The ELM Intercomparison, led by Ben Bond-Lamberty, is using ILAMB and other tools and metrics to identify optimal model configurations

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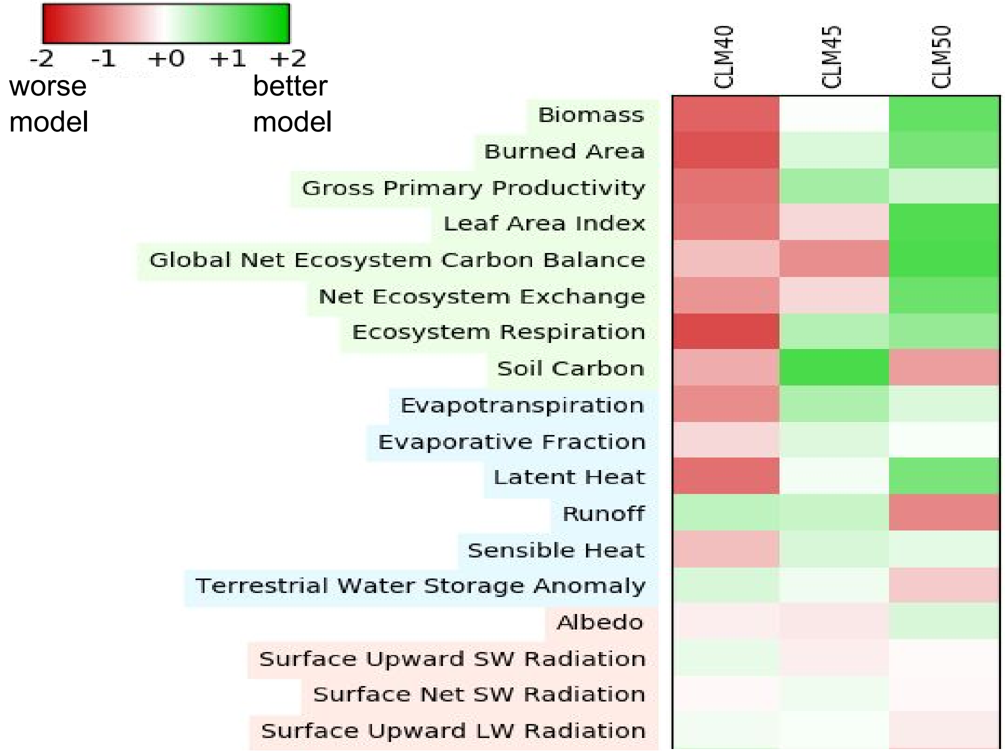
ILAMB assessing several generations of CLM



- ILAMB was used as an integral part of CLM5.0 development
- 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

ILAMB and IOMB Development

- Openly developed in Python using Git repository
  - https://bitbucket.org/ncollier/ilamb
  - Patches welcome! We have had features and bugfixes submitted by users
- Roughly biannual releases
  - v2.0 - May 2016
  - v2.1 - March 2017
  - v2.2 - November 2017
- Development activity
  - Develop new benchmarks for E3SM and modeling working groups
  - Adapt the ILAMB core to address community needs (ocean, high latitude, diurnal cycle)
  - Address computing environments and performance (laptops, clusters, NERSC, OLCF & ALCF)
  - Hone and improve the current methodology *with research community*
  - Continually improve documentation and tutorials (Provided at major meetings)
- Tracking use through software DOIs, workshop engagement, and interactive website visits — Many users will simply look at results!

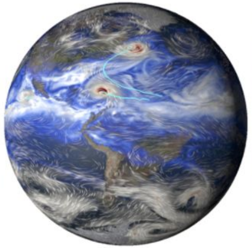
TECA: Toolkit for Extreme Climate Analysis

Home Abo... ...rces

The Toolkit for Extremes Climate Analysis

The Toolkit for Extremes Climate Analysis (TECA)

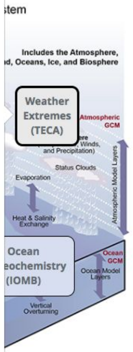
TECA is a high-performance, general purpose tool for detecting discrete weather events, such as tropical cyclones, in climate model output. Its core is a map-reduce framework, implemented in C++, that utilizes MPI and OpenMP parallelism. It features Python bindings for the core architecture, which allows rapid prototyping new detectors while taking advantage of the high-performance parallelism of the C++ core.



Quick links: Repository, Installation, and documentation

Coordinated Model Ev...

Coordinated Model Evaluation Capabilities (CMEC) is an effort to bring together a diverse set of analysis packages that have been developed to facilitate the systematic evaluation of Earth System Models (ESMs). Currently, CMEC includes three capabilities that are supported by the U.S. Department of Energy, Office of Biological and Environmental Research (BER), Regional and Global Climate Modeling Program (RGCM). As CMEC advances, additional analysis packages will be included from community-based expert teams as well a efforts directly supported by DOE and other US and international agencies.



A primary motivation for CMEC is to ana... ...ed to the Coupled Model Intercomparison Project (CMIP). ... ...ed in significant development of ESMs contributes simulations to CMIP. The 6th and latest phase (CMIP6; Meehl et al., 2014; Eyring et al., 2016) includes a partial but fundamental shift away from distinct CMIP phases with the advent of an ongoing core of benchmarking experiments known as the CMIP DECK (Diagnosis, Evaluation, Characterization of Klima – Klima being the German word for climate). The DECK includes a short list of experimental configurations that are routinely performed by ESM developers during their model development process. The DECK and "Historical" simulations provide a basis from which ESMs can be compared with available observations.

To date, many ad hoc analysis packages have been developed to target selected aspects of ESM simulations. With the growing scope of CMIP and expectations for efficient "quick look" results, there is a clear need for the community of CMIP analysts to work together. CMEC is establishing a framework for the developers of these capabilities to collaborate and to deliver a unified set of results.

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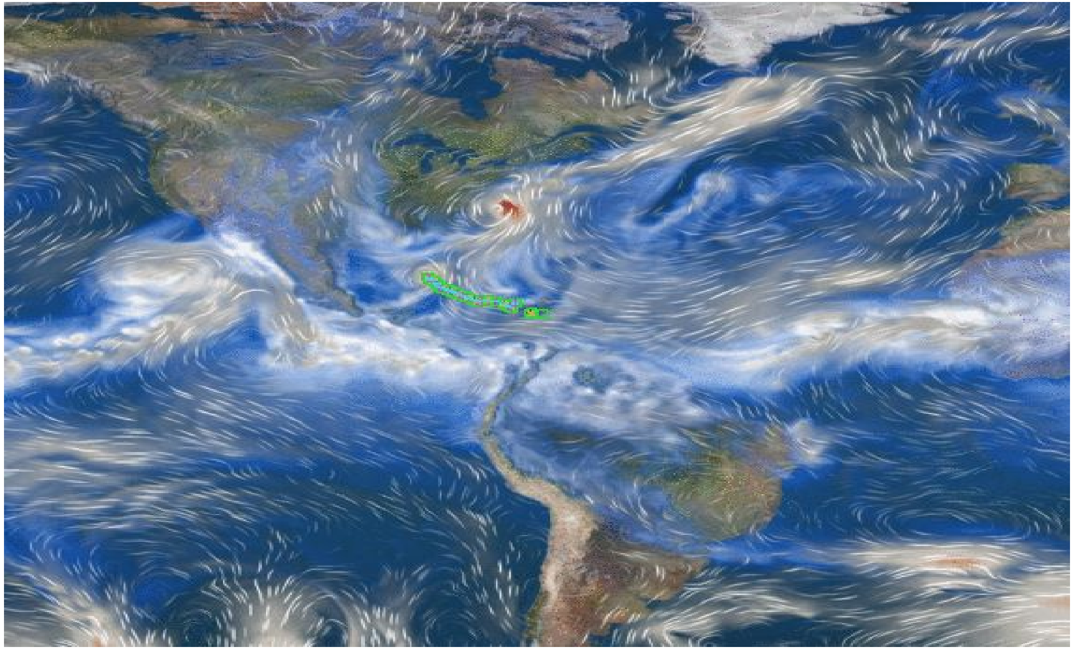
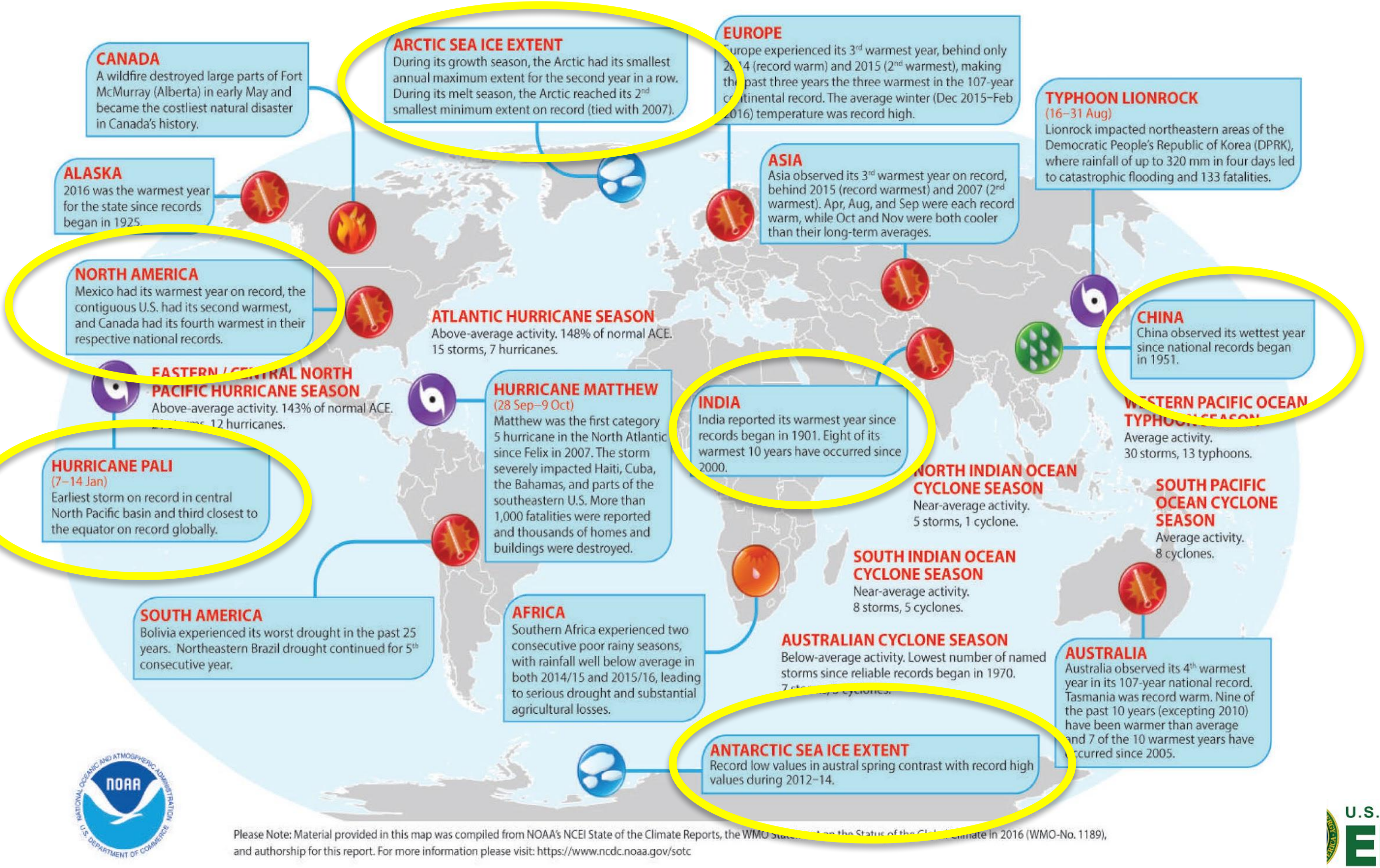
TECA: Toolkit for Extreme Climate Analysis

- TECA is a tool for detecting discrete weather events in climate output.
- The main use case is for research on extremes…



CMEC

2016 was an eventful year for extreme weather



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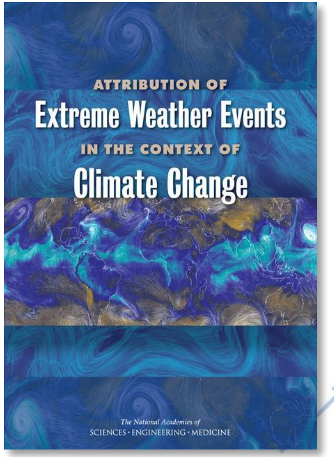
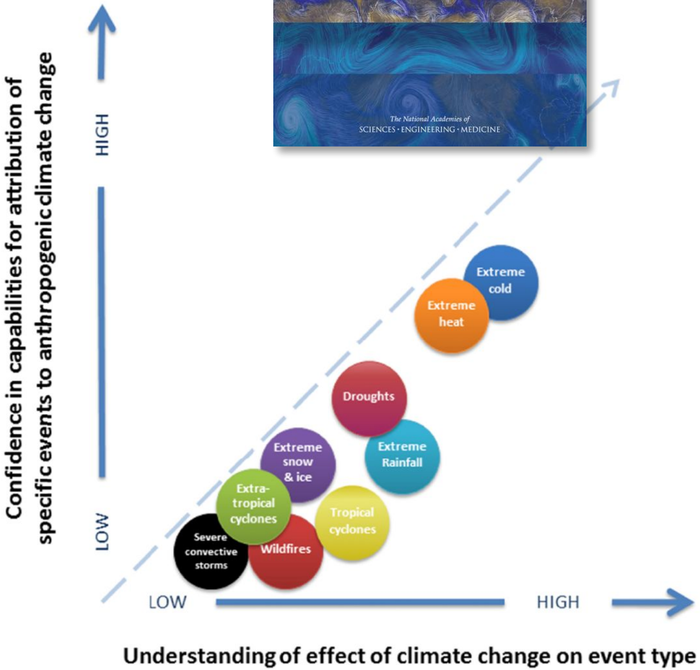
CMEC



● = high ◉ = medium ○ = low	Capabilities of Climate Models to Simulate Event Class	Quality/Length of the Observational Record	Understanding of Physical Mechanisms that Lead to Changes in Extremes as a Result of Climate Change
Extreme cold events	●	●	●
Extreme heat events	●	●	●
Droughts	◉	◉	◉
Extreme rainfall	◉	◉	◉
Extreme snow and ice storms	◉	○	◉
Tropical cyclones	○	○	◉
Extratropical cyclones	◉	○	○
Wildfires	○	◉	○
Severe convective storms	○	○	○



*"Bringing multiple scientifically appropriate approaches together, including **multiple models** and **multiple studies** helps distinguish results that are robust from those that are much more sensitive to how the question is posed and the approach taken."*

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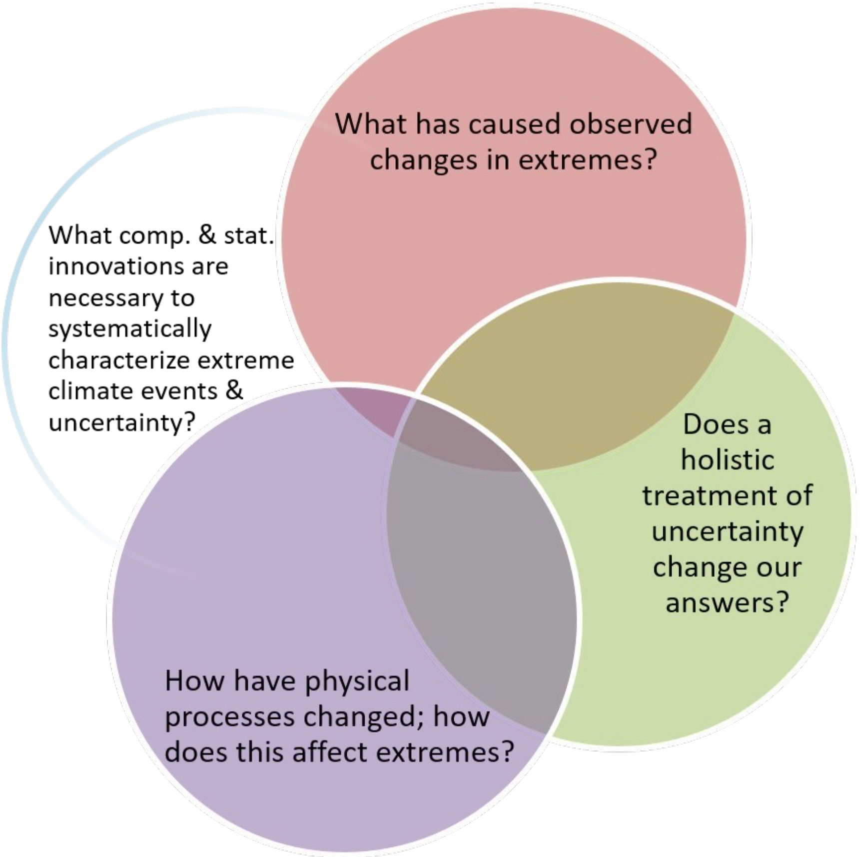
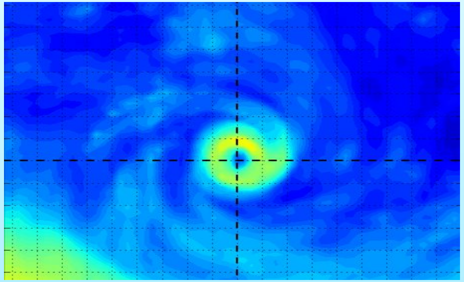
CASCADE Key Questions



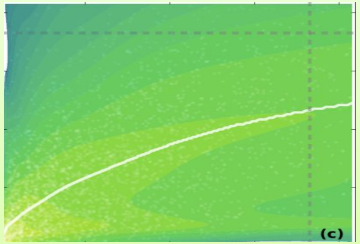
CASCADE Produces Community Data Analysis Tools

TECA
bitbucket.org/lbl-cascade/teca



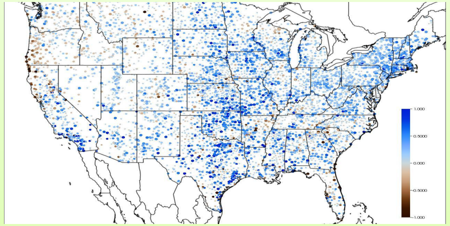
- Fast, scalable event detection
- TC, AR, and ETC detection
- Python API for add'l algorithms

fastKDE
dist. via *bitbucket* and *pip*



- Fast, robust PDF estimation
- Multidimensional

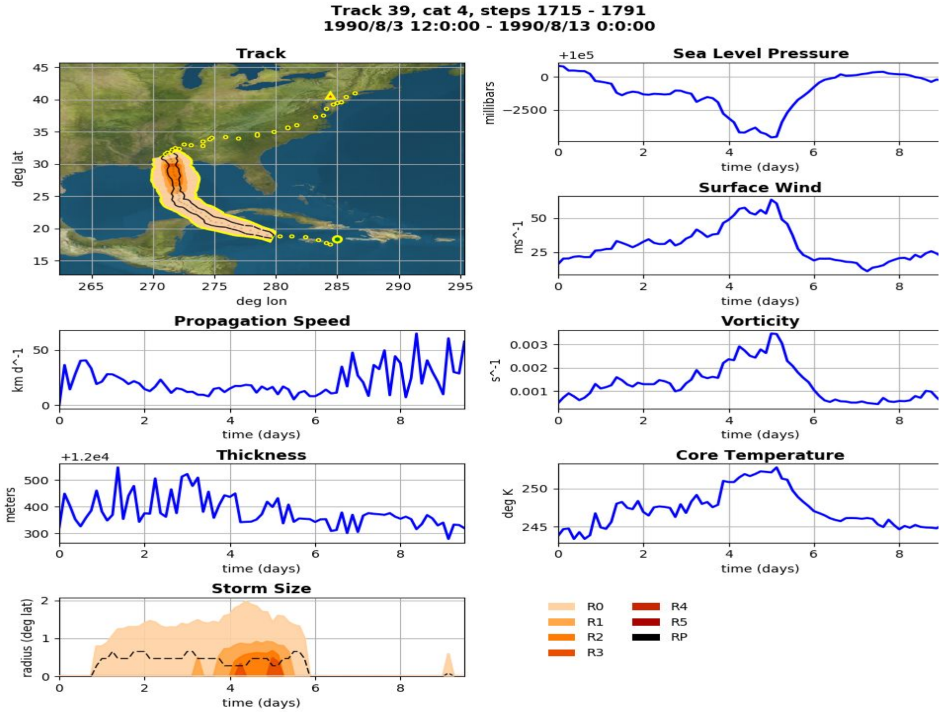
climextRemes
dist. via *CRAN* & *UV-CDAT*



- Flexible extreme value analysis
- R and Python packages

TECA: Toolkit for Extreme Climate Analysis

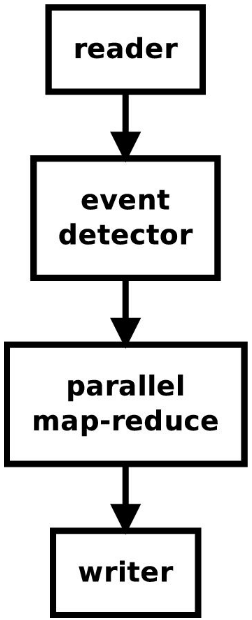
- Detects extreme weather events
- Leverages map-reduce framework:
  map—candidate detection
  reduce—stitch paths
- Efficient and highly parallel: analyzed extratropical cyclones in all of CMIP5 in 1 hour
- Python interface for rapid detector prototyping



Download at https://github.com/LBL-EESA/TECA

TECA2: A platform for feature detection/classification

- TECA2 allows *easy exploration* of existing algorithms, and construction of new ones.
- Simple input machinery allows easy tuning and analysis of parameters
- “Snap-together” pieces form high-performance pipelines that can execute on DOE’s HPC platforms
    - Several **reusable** components fit into multiple pipelines
    - Components and pipelines can be built using **Python**
- TECA2’s parallelism is best-in-class (MPI + threads): **makes efficient use of Cori KNL.**



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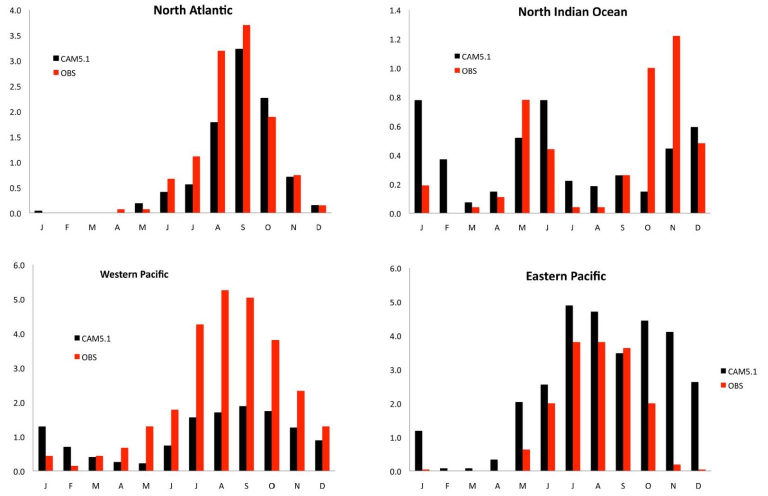
Evaluating TC Statistics in Climate Models



Objective: Objectively assess what is to be gained from high horizontal resolution in the Community Atmospheric Model, CAM5.1 enabled by current generation DOE supercomputers.

Research: At resolutions of 25km, global atmospheric models realistically simulate many types of extreme weather. We find that fvCAM5.1 reproduces observed hurricane frequencies and intensities. Furthermore, the model more accurately simulates extreme daily precipitation than CMIP5-class models.

Impact: High resolution climate models provide new capabilities to examine future changes in extreme storms and precipitation in ways that the CMIP5 models cannot. As high resolution models become mainstream, confidence in projected changes in extreme weather will be increased.

TECA's Userbase

- A tiered system for supporting DOE science and the broader community:
    - CASCADE researchers
    - DOE Collaborators (Hyperion, University projects)
    - Broader community

TECA’s value within DOE

- Capability to analyze extremes w/ a focus on events that matter for natural and managed systems: especially energy and water
- Allows a process/phenomena focused analysis of extremes
- Permits analysis of DOE model biases, focused on the actual weather events that bring biases: e.g., Western US precip biases and ARs

TECA's value within broader community

- Capability to analyze extremes with a focus on events that matter for natural and managed systems
- Allows a process/phenomena-focused analysis of extremes
- Permits analysis of climate model biases, focused on the actual weather events that bring biases

Variability, Extremes, and Biogeochemical Cycles

CMEC

Coordinated Model Evaluation Capabilities

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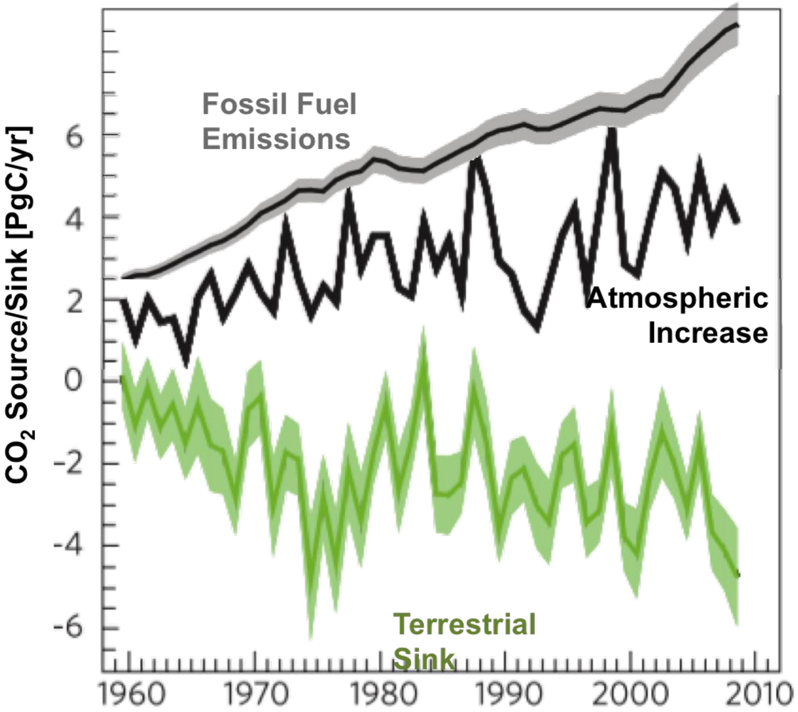
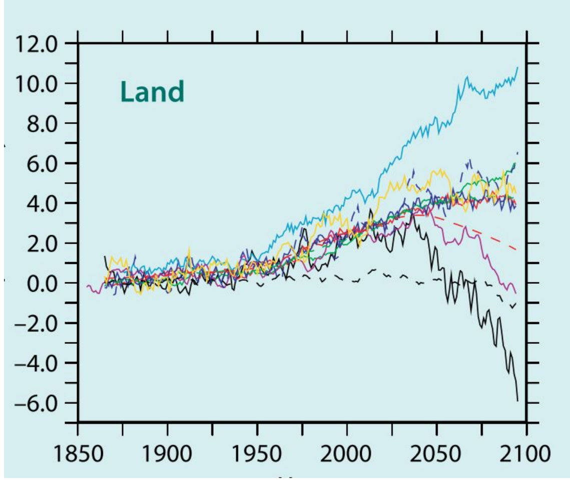
The critically important *terrestrial sink:* a major source of uncertainty



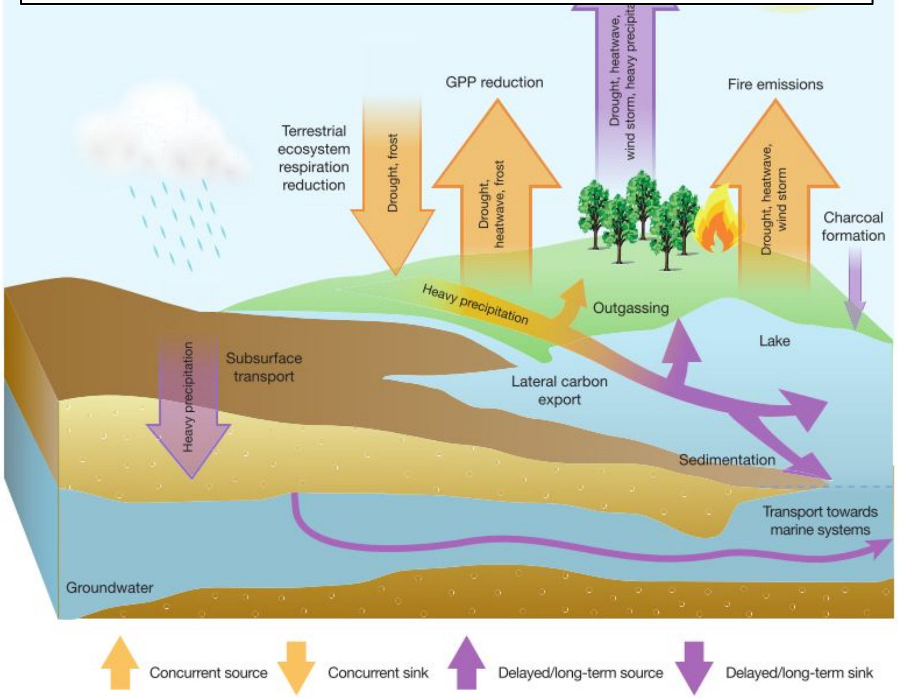


Adapted from U.S. DOE, 2008: Carbon Cycling and Bio-sequestration: Report from the March 2008 Workshop. 141 pp.

Adapted from Le Quéré, C. et al., 2009. Nat. Geosci., 2, 831–836, doi:10.1038/ngeo689

Extremes: an enormous impact on the carbon cycle

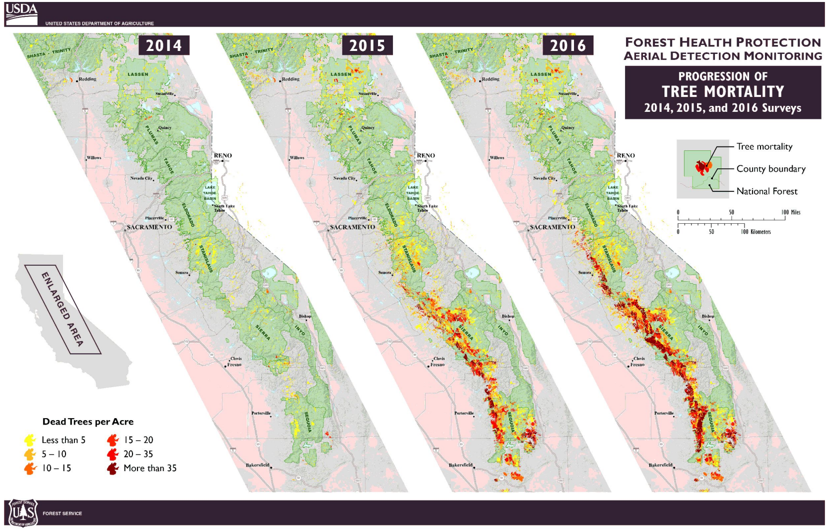
3—10 PgC/yr effect on GPP
from extremes!



Reichstein, M. et al., 2013. Nature, doi:10.1038/nature12350

Koven ECRP: Understanding how climate extremes govern terrestrial feedbacks in Western US

- Droughts and other climate extremes can lead to dramatic **restructuring of ecosystems** via vegetation mortality and range shifts, with long-term consequences to ecosystem function that govern feedbacks.
- Current “big-leaf” and static vegetation models don’t include these linkages, but **demographic and dynamic vegetation models** such as FATES do.
- Extreme events like the recent CA drought allow opportunity to **benchmark** the processes in these models.



USFS Aerial Tree Mortality Survey, 2016

Shifts in biomass and productivity for a subtropical dry forest in response to simulated elevated hurricane disturbances

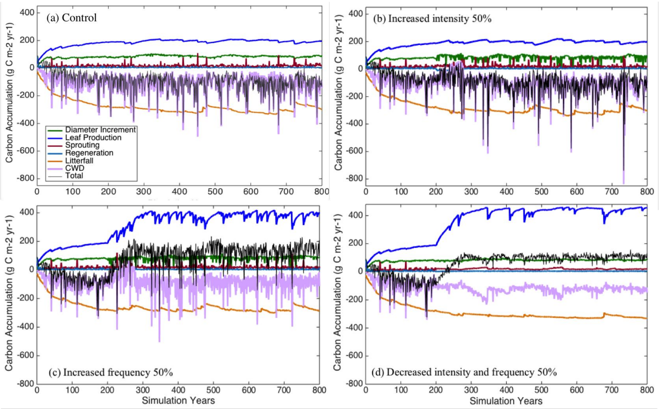


Fig.1 Shifts in six carbon components compared to historical hurricane regimes (control), with the total accumulation switching to positive (i.e. sink) in the bottom panels.

Scientific Achievement

- This model-based investigation assessed the impacts of storms of elevated intensities and frequencies on the long-term carbon dynamics of a subtropical dry forest in Puerto Rico.
- This is the first attempt to model hurricane effects for *dry* forests of Puerto Rico; a unique, overlooked, and threatened biome of the world.

Significance and Impact

- Fig. 1c = More frequent storms (*which remained at current intensity*) led to a switch in simulated carbon accumulation from negative to positive (i.e. sink).
- We predict the long-term forest structure and productivity will not be largely affected in relationship to storm *intensity* alone.
- These results and methodology are being considered for DOE's new dynamic vegetation model FATES, which is being integrated into ALMv1.

Research Details

- This study uniquely utilized local forest inventory measurements that were recorded before and after a hurricane event. This allowed for the creation of realistic species-specific model damage classes and a new disturbance damage routine, which were used in a dynamic vegetation forest gap model (ZELIG-TROP).
- This research allowed for the investigation of shifts in individual carbon components (see Fig. 1)

Holm, J.A., S.J. Van Bloem, G.R. Larocque, and H.H. Shugart. Shifts in biomass and productivity for a subtropical dry forest in response to simulated elevated hurricane disturbances. Environ. Res. Lett. 12; 025007 (2017).

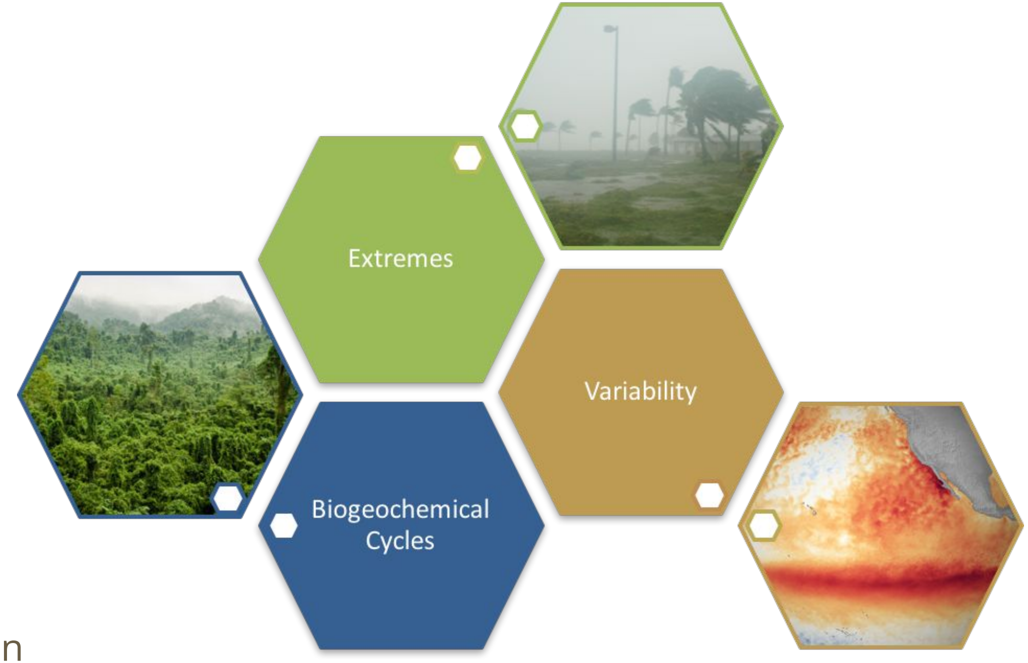
Quantifying errors in variability, extremes, and biogeochemical cycles

Need:

- Huge uncertainty in terrestrial sink
  - *effects on future biogeochemical cycles unknown, but possibly huge*
- Major, documented effect of extremes on carbon storage
- Extremes are modulated by variability and mean climate state

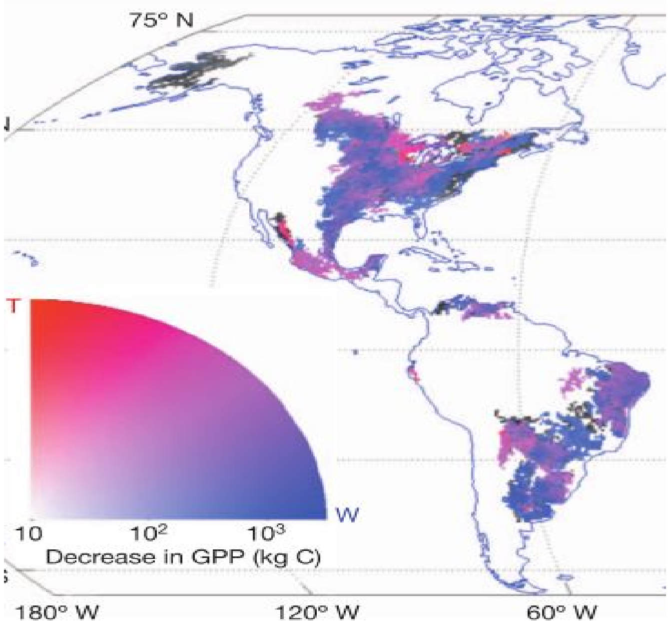
Major Questions:

- How do errors in mean climate and variability relate to errors in extremes?
- How do errors in extremes relate to errors in biogeochemical cycles?
- How do errors in biogeochemical cycles relate to errors in climate?



Answering these questions requires a new type of tool

- These questions are linked and may constitute a feedback system that amplifies model errors
- A tool is needed that permits simultaneous assessment of:
  - Climate and climate variability
  - Statistics of extreme events
  - Biogeochemical cycles

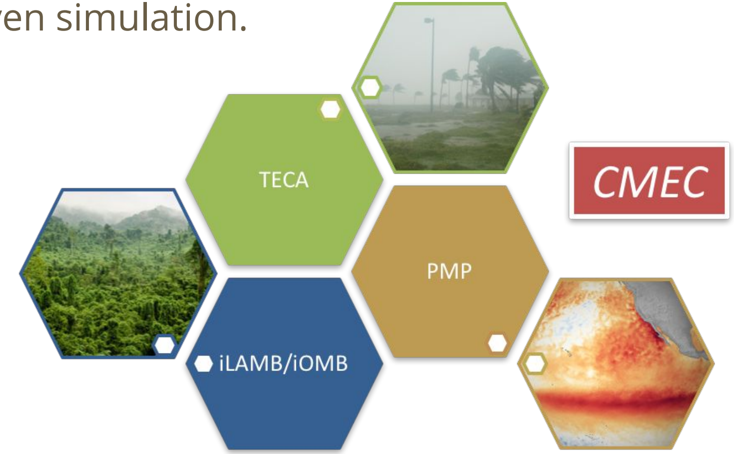


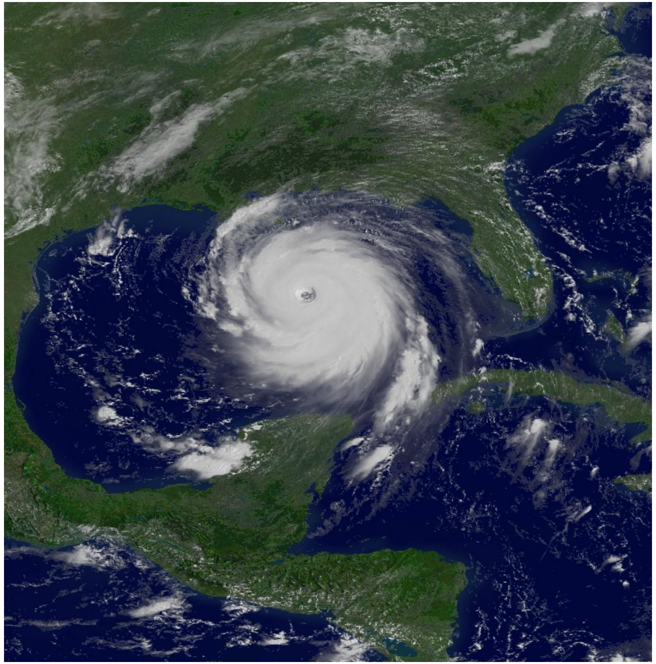
Reichstein, M. et al., 2013. Nature, doi:10.1038/nature12350

CMEC Provides a Low Cost Path Forward

CMEC Component	Role
PMP	Quantify errors in mean and variability
TECA	Quantify errors in extremes
ILAMB/IOMB	Quantify errors in BGC cycles

CMEC could provide a simple, federated tool for simultaneously characterizing climate, extremes, and BGC cycles in a given simulation.





A prototype set of hypotheses for E3SM

- Errors in ENSO+AMO cause errors in TC statistics
- Errors in TC statistics cause errors in terrestrial tropical and subtropical carbon stores
- Errors in terrestrial carbon stores cause errors in mean climate that project onto errors in ENSO+AMO

CMEC Component	Role
PMP	Quantify errors in climate, ENSO, AMO
TECA	Quantify errors in tropical cyclone statistics/characteristics
ILAMB/IOMB	Quantify errors in tropical/subtropical carbon stores

CMEC beyond a prototype experiment

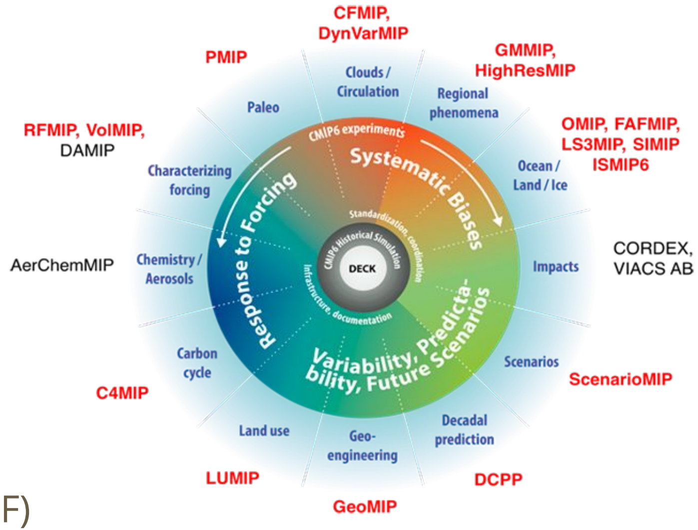
- Target audiences:
  - E3SM community: particularly critical for FATES-based versions w/ variable resolution
  - International climate community: hi-res coupled simulations will become common in 5-10 year timeframe

PMP-ILAMB-IOMB-TECA synergies

- Exploring scientific linkages will be an integral part of CMEC research and will provide a unique set of CMIP6 synthesis papers
- Establishing CMEC protocols is an ongoing collaborative effort
- Content and objectives are highly complementary, with nominal overlap to routinely verify techniques

Coordination within CMEC

- PMP, ILAMB, IOMB, and TECA currently
  - Follow netCDF Climate and Forecast (CF) conventions for reading/writing data
  - Utilize CMIP variable naming and units conventions
  - Written in Python or provide a Python interface
  - Use Git via GitHub or BitBucket for open access
- Continued coordination will focus on CMIP6
  - Evaluation of CMIP6 results:
    - PMP: Historical and DECK Experiments
    - ILAMB: Historical, C^4MIP, LUMIP, LS3MIP
    - IOMB: Historical, C^4MIP, OMIP
    - TECA: HighResMIP
  - Connections with the Earth System Grid Federation (ESGF)
    - Automated retrieval of model results for benchmarking and diagnosis
    - Advertising CMEC results from the ESGF portals (look before you leap/download)
    - Offering data ordering options from within diagnosis pages
  - Share and leverage interface designs and processing methods



CMEC

Coordinated Model Evaluation Capabilities

U.S. DEPARTMENT OF ENERGY