Lawrence Livermore National Laboratory

PCMDI

Earth System Model Evaluation Project

Paul Ullrich
Celine Bonfils
Paul Durack

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Jiwoo Lee
Hsi-Yen Ma

Po-Lun Ma
Steve Po-Chedley
Mark Zelinka

LLNL-PRES-865204

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EESM PI Meeting
August 2024

PCMDI Overview

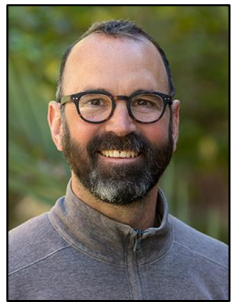
- PCMDI is among the most recognized names in the climate science community, with a long and established history tackling the science of climate change.
- PCMDI is a hub for climate research in the DOE and beyond. The project has extensive expertise with data standards, model evaluation, and experiment design. PCMDI's efforts have been responsible for accelerating climate research around the world.
- PCMDI are leaders in the global climate research community, with contributions to the Intergovernmental Panel on Climate Change since its inception.

Current Personnel

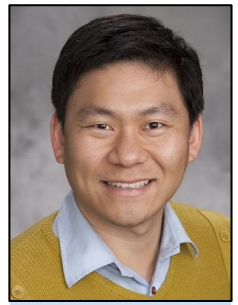
Elizabeth Barnes (CSU)

Celine Bonfils

Paul Durack



Alex Hall (UCLA)



Jiwoo Lee

Hsi-Yen Ma

Po-Lun Ma (PNNL)

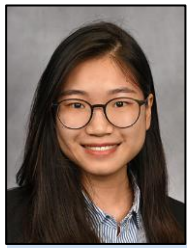
Steve Po-Chedley

Paul Ullrich

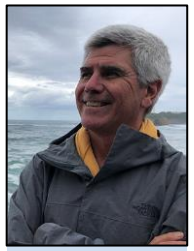
Mark Zelinka

Sasha Ames

Kristin Chang



Li-Wei Chao



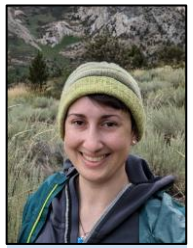
Peter Gleckler

Anthony Hoang

Steve Klein

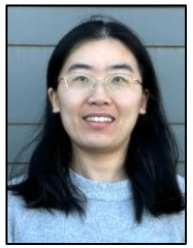
Chris Mauzey

Jesse Norris (UCLA)

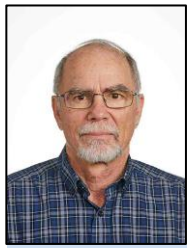


Ana Ordonez

Giuliana Pallotta



Yi Qin (PNNL)



Karl Taylor

Chad Thackeray (UCLA)

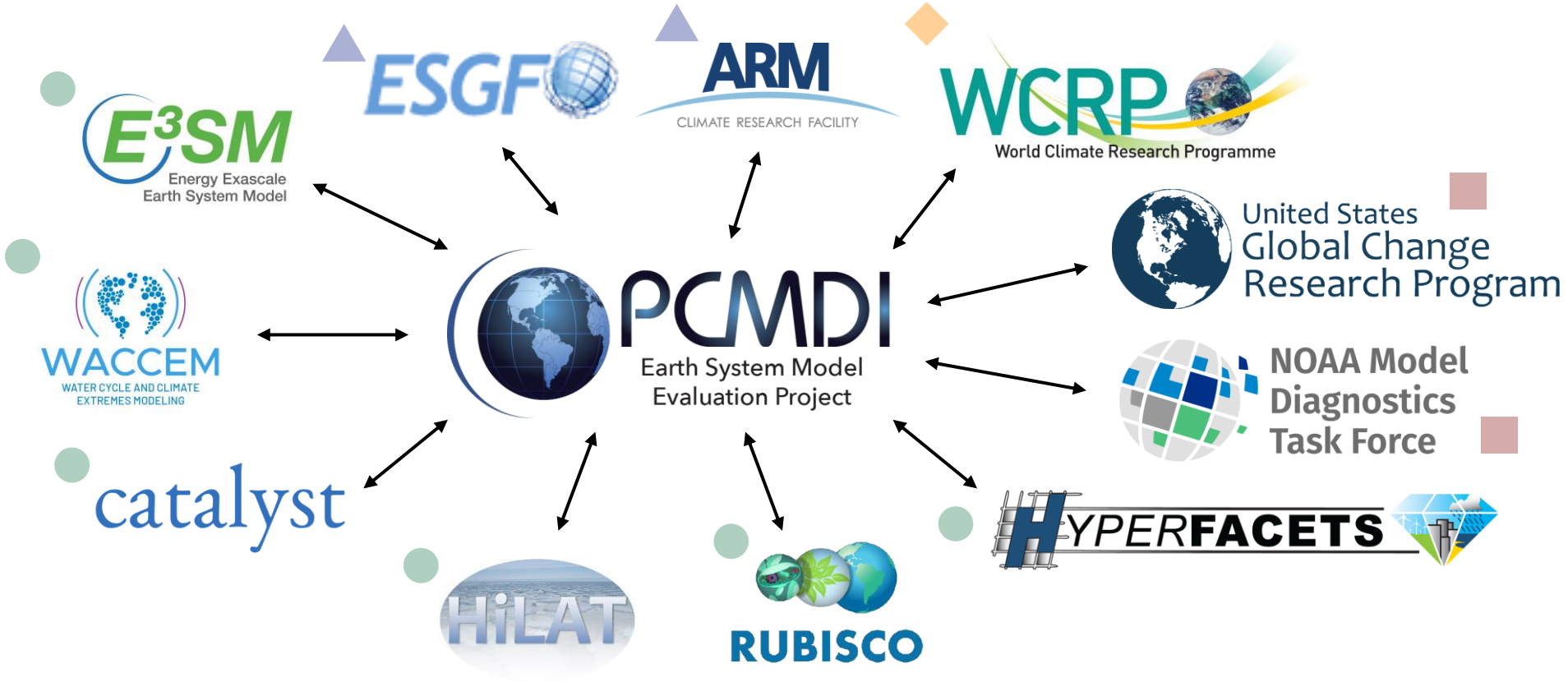
Shading indicates LLNL affiliation

PCMDI supports a broad mix of expertise across all career levels

Hub and Spoke: Active Collaborations

PCMDI is a hub for climate data and expertise at regional, national and international levels.

- US DOE Earth and Environmental Systems Modeling
- US DOE Biological and Environmental Research
- Interagency
- International



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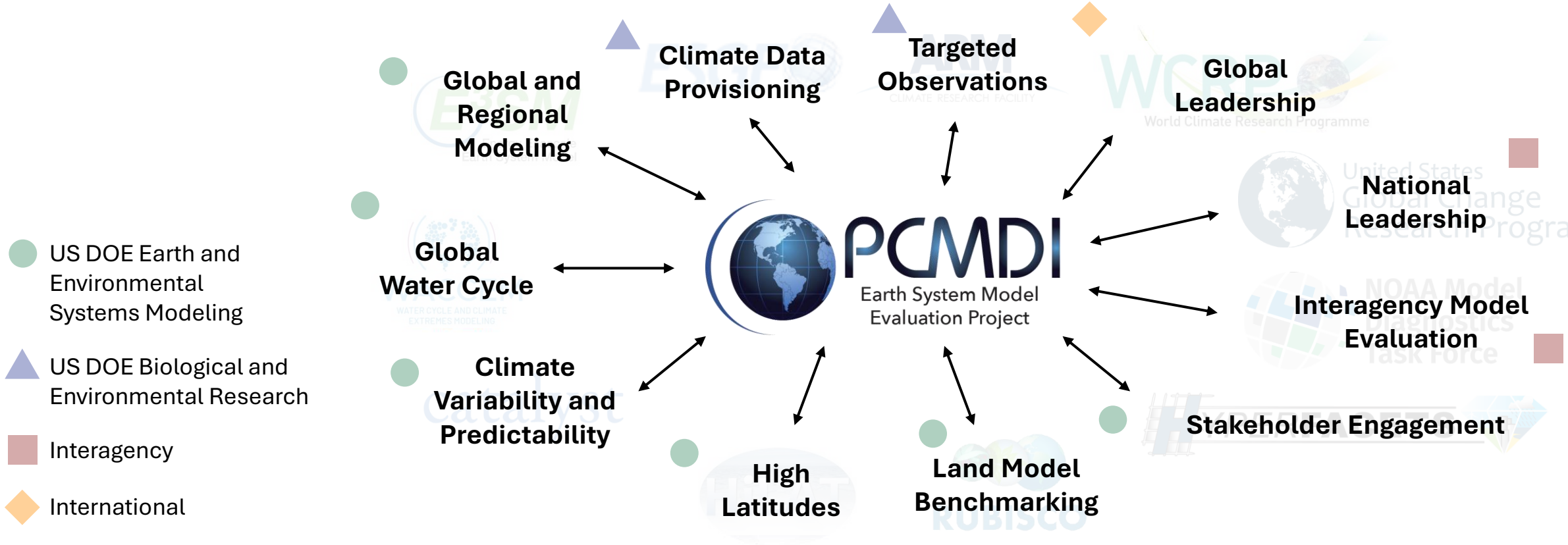


PCMDI
Earth System Model Evaluation Project

Our Goal

To quantify and constrain uncertainties in our understanding of Earth system variability, forcing and response

Project Structure

Scientific Discovery

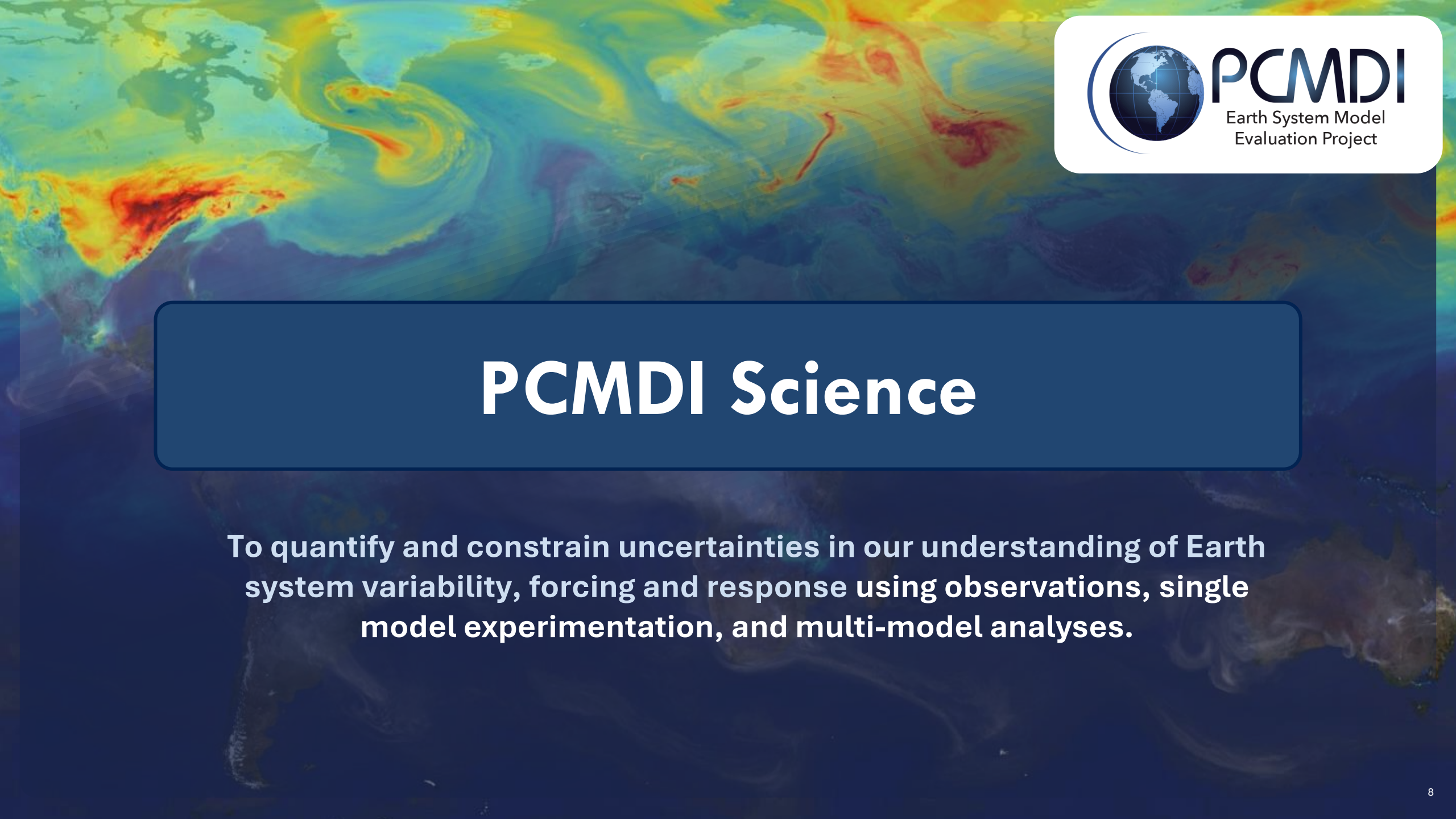
Cloud feedbacks and climate sensitivity; interpreting Earth system changes; pattern effects

Capabilities and Support

Software, tools and capabilities to accelerate and support research in DOE and beyond

National and International Leadership

Leading the science, design, and implementation of model intercomparison

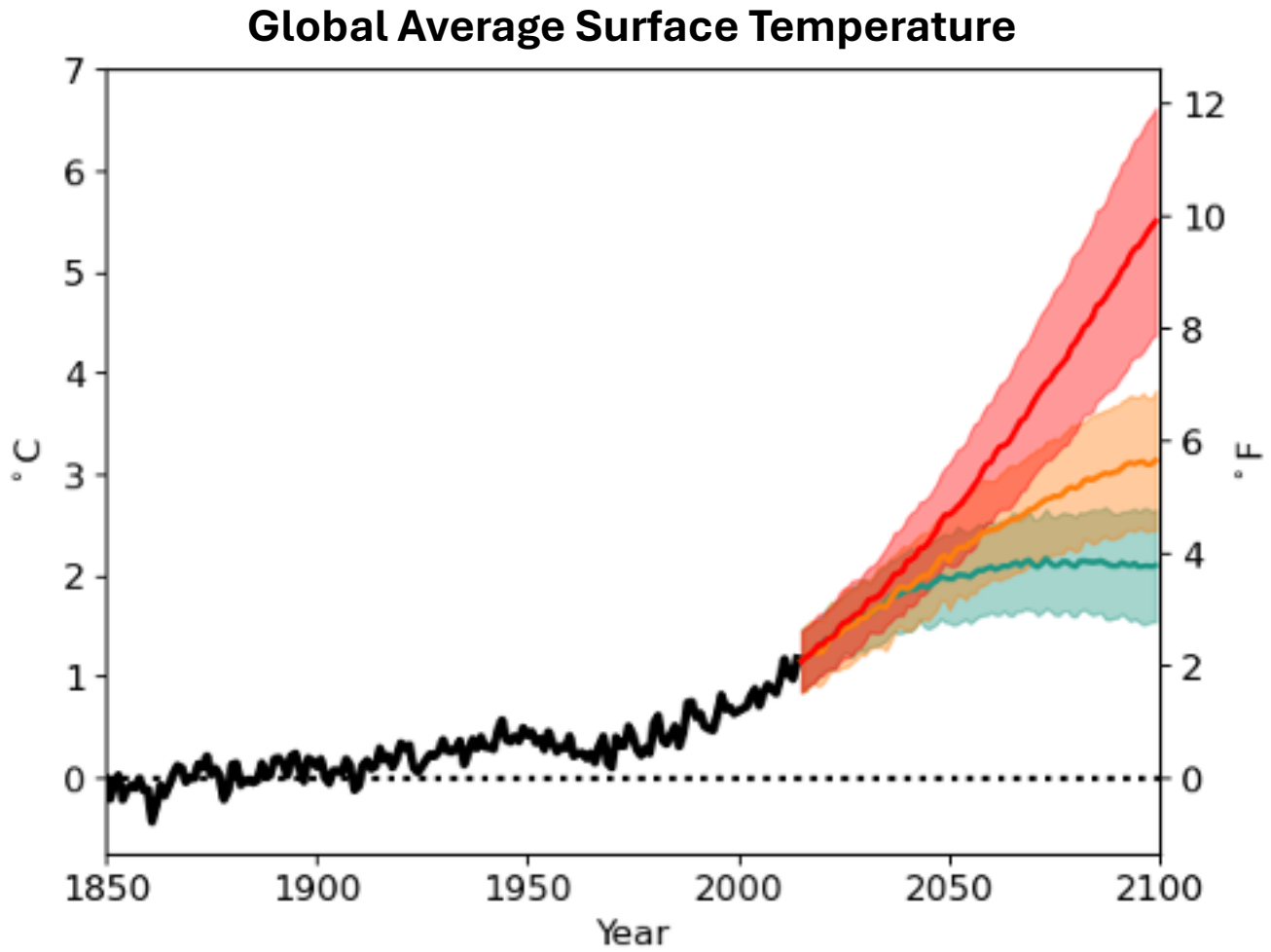


PCMDI
Earth System Model Evaluation Project

PCMDI Science

To quantify and constrain uncertainties in our understanding of Earth system variability, forcing and response using observations, single model experimentation, and multi-model analyses.

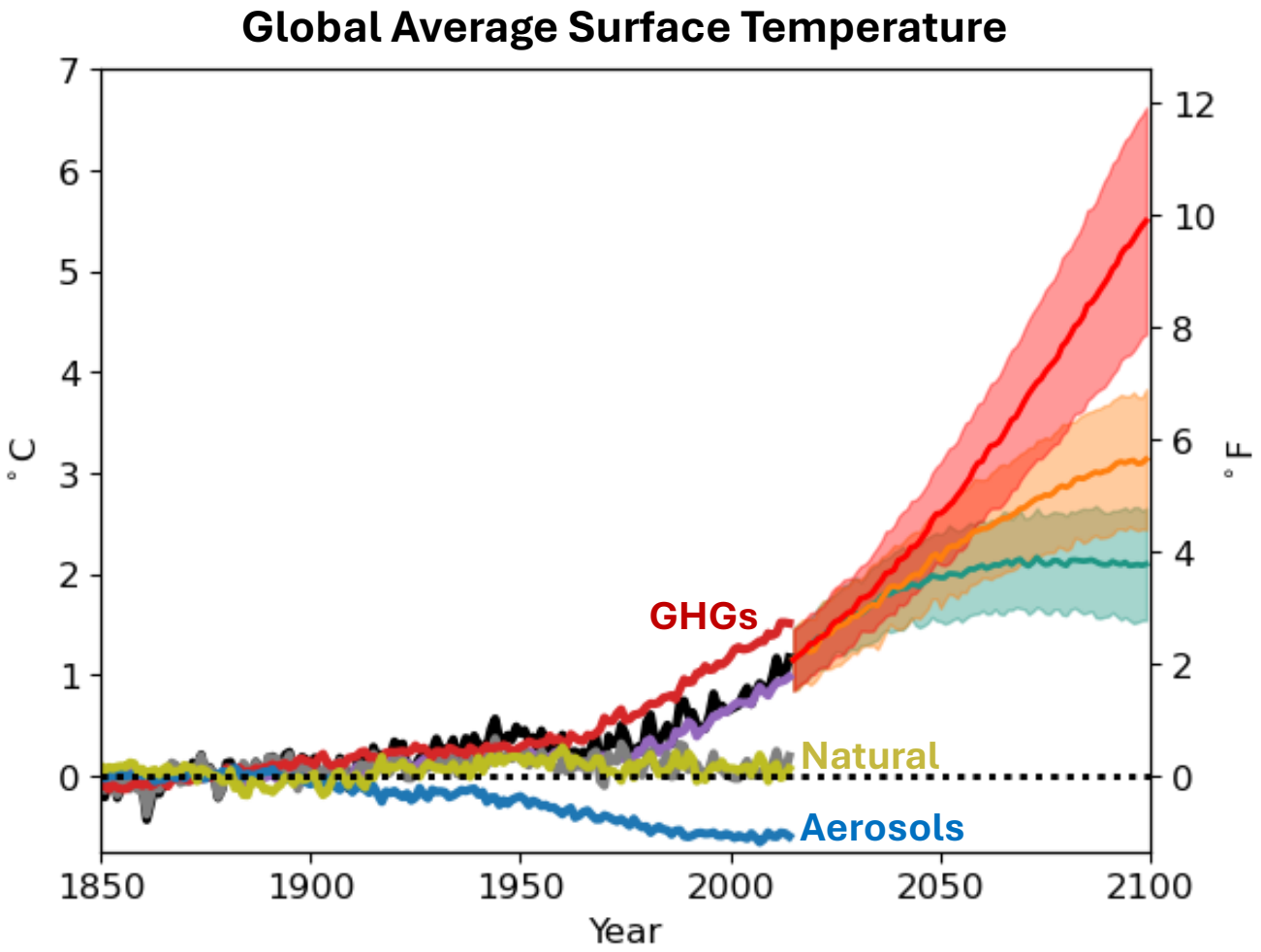
Key Climate Uncertainties



Future warming depends on climate sensitivity, which is uncertain primarily because of radiative feedbacks, particularly those involving clouds. ***How can we constrain cloud feedbacks?***

Key Climate Uncertainties

Knowledge of the past can only inform the future if properly interpreted. Past climate change is due to an unknown mix of greenhouse gas warming opposed by aerosol forcing, all occurring in a cacophony of natural variability. ***How to extract these distinct signals?***



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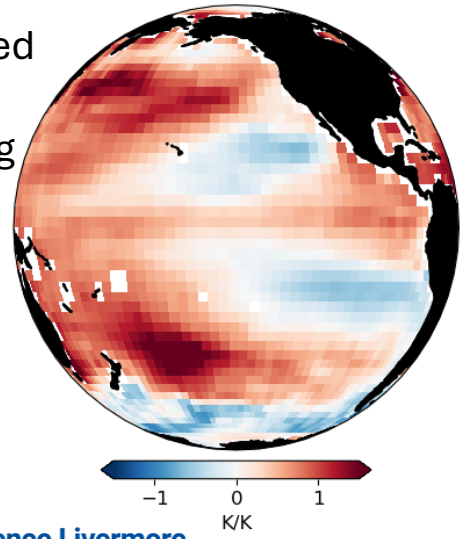
Key Climate Uncertainties

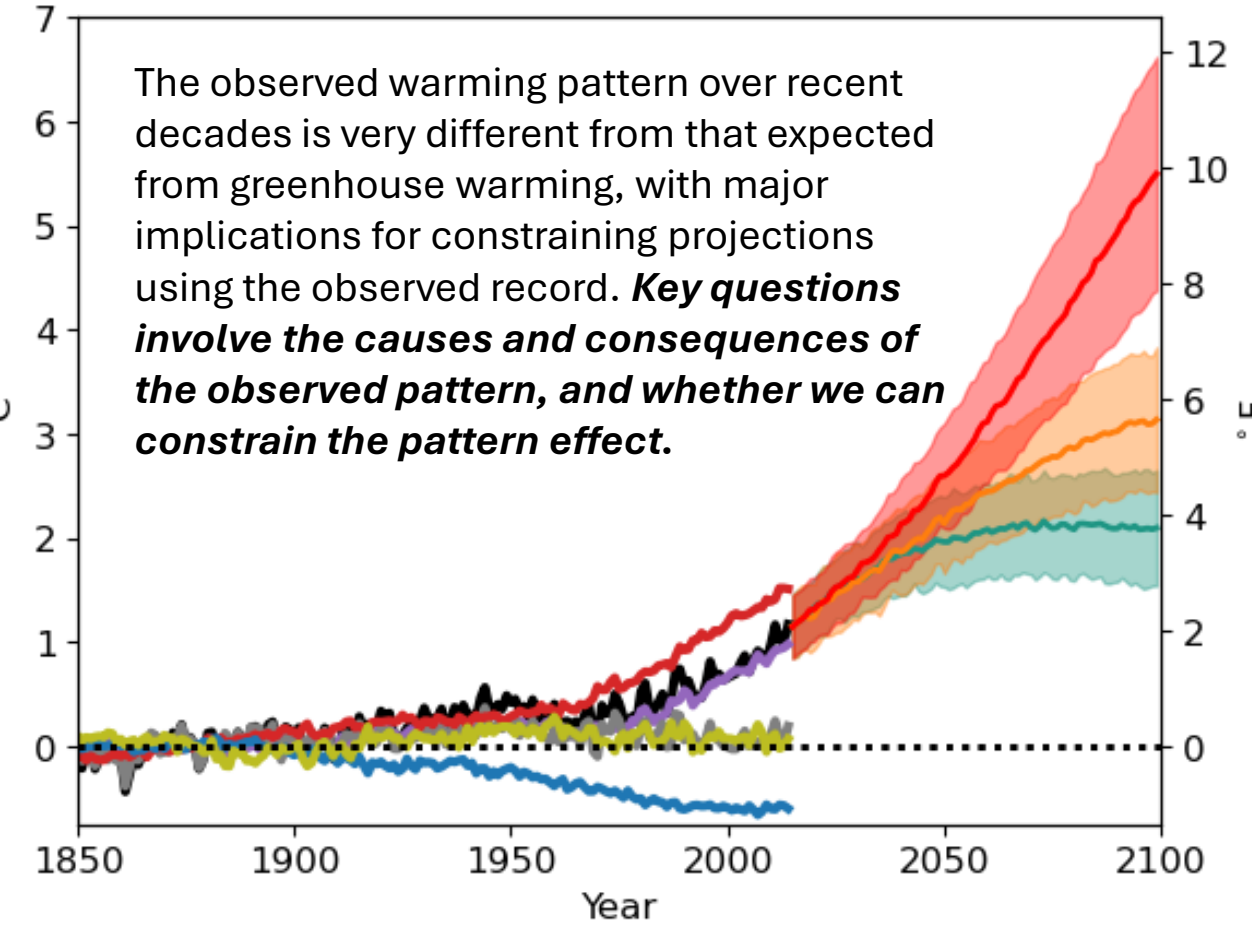
Knowledge of the past can only inform the future if properly interpreted. Past climate change is due to an unknown mix of greenhouse gas warming opposed by aerosol forcing, all occurring in a cacophony of natural variability. **How to extract these distinct signals?**

Observed recent warming pattern

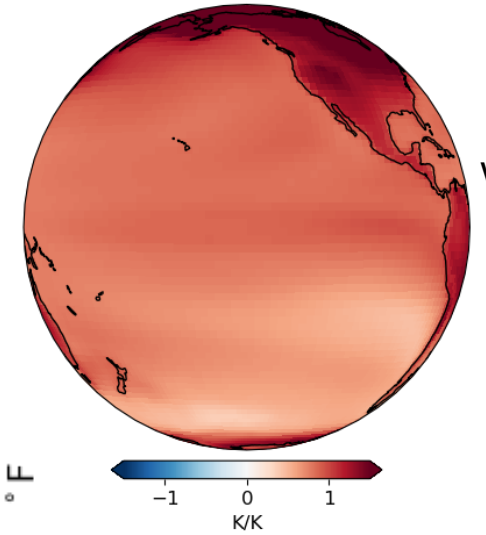


Global Average Surface Temperature

The observed warming pattern over recent decades is very different from that expected from greenhouse warming, with major implications for constraining projections using the observed record. ***Key questions involve the causes and consequences of the observed pattern, and whether we can constrain the pattern effect.***



Modeled future warming pattern



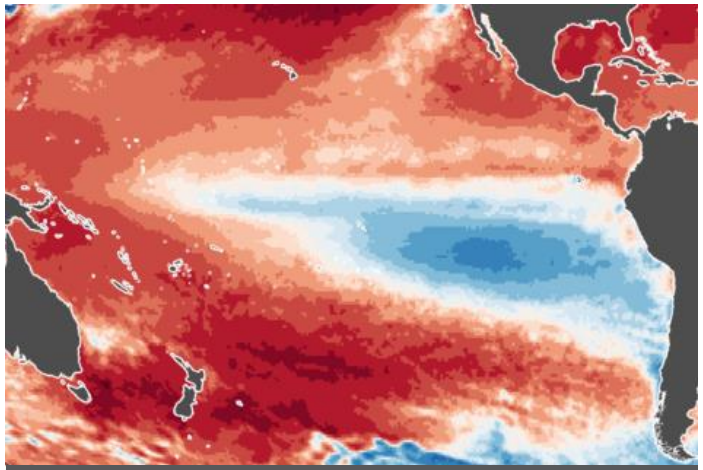
Future warming depends on climate sensitivity, which is uncertain primarily because of radiative feedbacks, particularly those involving clouds. ***How can we constrain cloud feedbacks?***

Lawrence Livermore National Laboratory

Three Scientific Foci

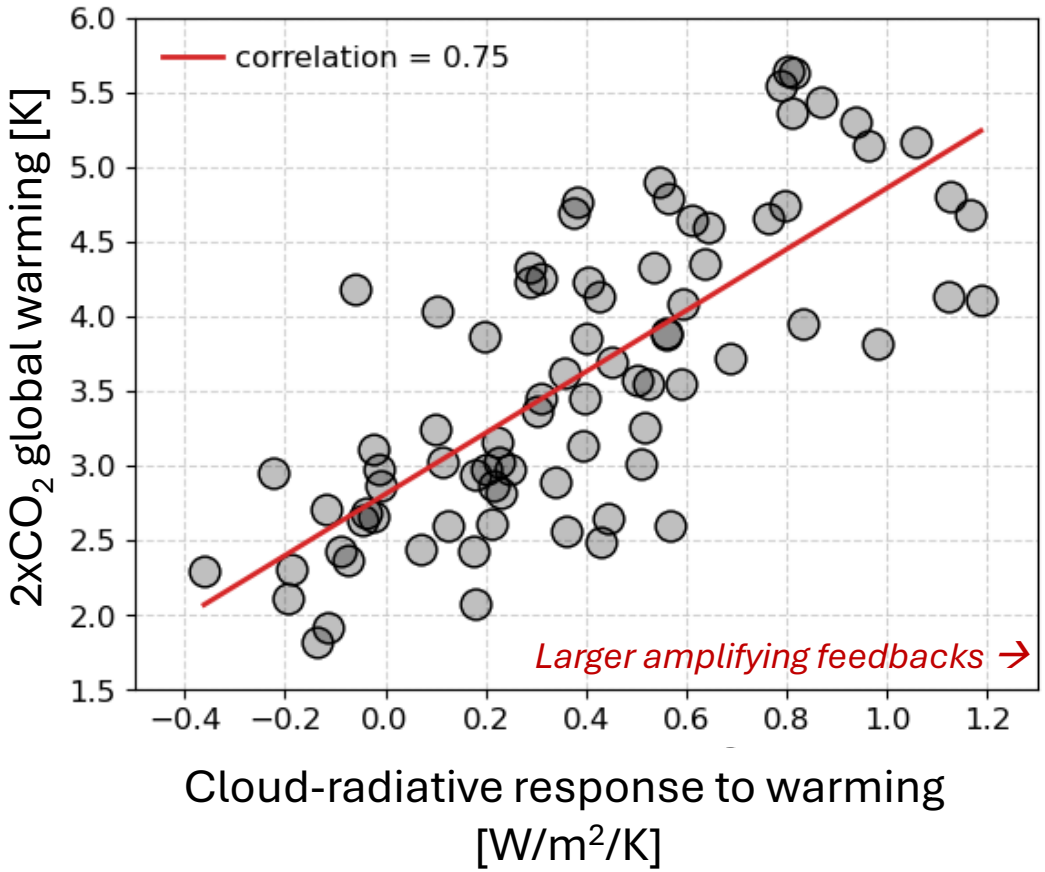
Cloud Feedbacks and Climate Sensitivity

Detection, Attribution, and Disentanglement



Pattern Effects

Uncertainty in future global warming comes from uncertainty in how clouds respond to warming



- We have pioneered techniques for quantifying cloud feedbacks and separating them into components arising from physical processes.
- This has led to improved understanding of where the uncertainties lie, which responses are robust across models, and where models are biased with respect to observations.
- In a highly cited 2020 paper (*>1000 citations*) we have leveraged these tools to reveal reasons why the latest climate models have larger climate sensitivities than their predecessors, identifying the source of the "hot model" problem.

Our work has been highly influential in identifying the processes causing inter-model spread in forcing, feedbacks, and climate sensitivity.

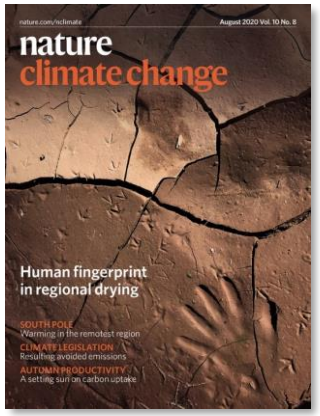
Disentangling forced and unforced climate signals with machine learning

- We are leveraging our expertise in anthropogenic signal detection, augmented with novel machine learning techniques, to tackle new challenges (and some old ones in new ways).
- Using machine learning applied to large ensembles of model simulations, we have separated human vs. natural causes of recent atmospheric warming trends.
- This reveals that natural variability has substantially reduced recent warming, helping to explain why satellite observations show less warming than climate model simulations – a longstanding discrepancy.

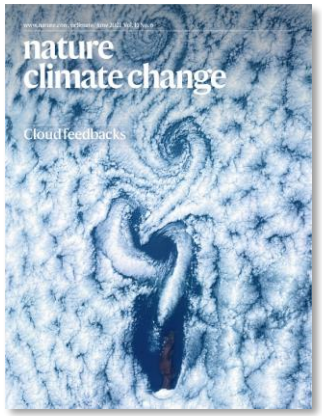
Atmospheric temperatures measured by satellites warm less than simulated by climate models. New techniques reveal that internal climate variations are partly responsible.

We are advancing new techniques for disentangling climate signals from each other and using them to improve understanding of past climate change and its implications for the future.

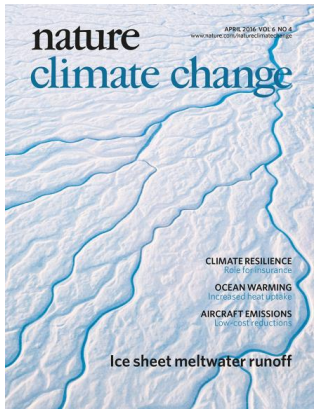
Recent Attention



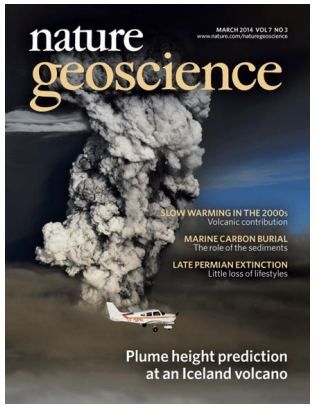
Bonfils et al. 2020
Human fingerprint in regional drying



Myers et al. 2021
Constraints on marine low-cloud feedback

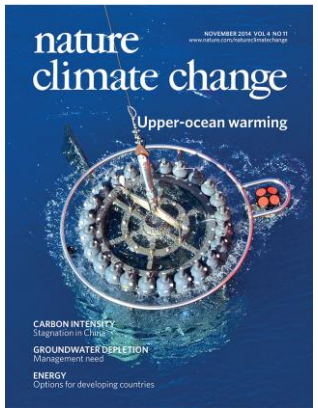


Gleckler et al. 2016
1/3 of warming occurs below 700m in ocean



Santer et al. 2014
Volcanic eruptions

Röthig et al. 2023
Salinity's role in ocean biogeochemistry



Röthig et al. 2023
Salinity's role in ocean biogeochemistry

Geophysical Research Letters

Causes of Higher Climate Sensitivity in CMIP6 Models

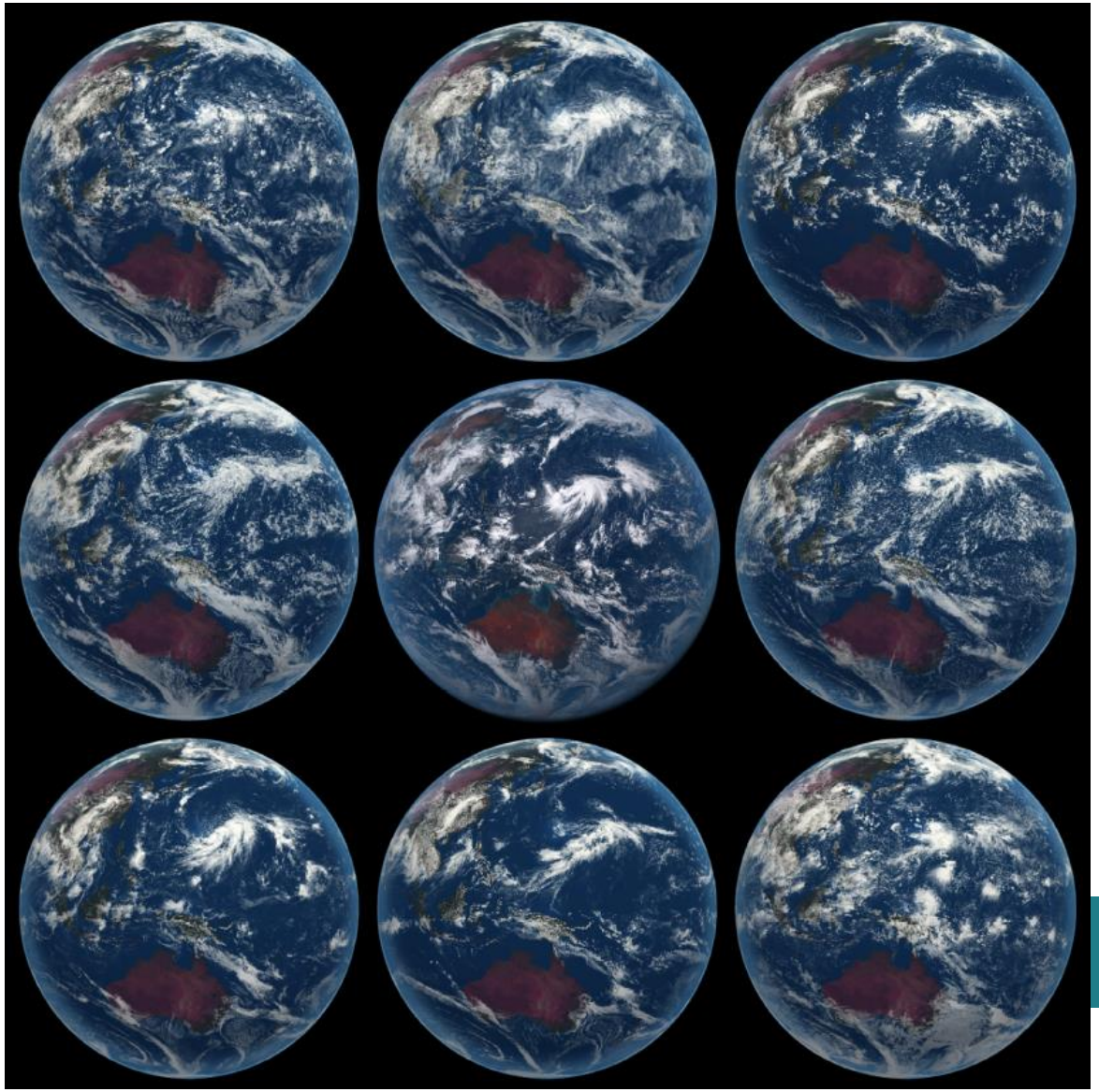
Mark D. Zelinka[1], Timothy A. Myers[1], Daniel T. McCoy[2], Stephen Po-Chedley[1], Peter M. Caldwell[1], Paulo Ceppi[3], Stephen A. Klein[1], and Karl E. Taylor[1]

[1]Lawrence Livermore National Laboratory, Livermore, CA, USA, [2]Institute of Climate and Atmospheric Sciences, University of Leeds, Leeds, UK, [3]Grantham Institute, Imperial College London, London, UK

Zelinka et al (2020), **cited more than 1000 times**, was recently showcased as **"Editor's Choice" paper**: one of the highest achieving papers that have been published in *Geophysical Research Letters* over its 50-year existence.

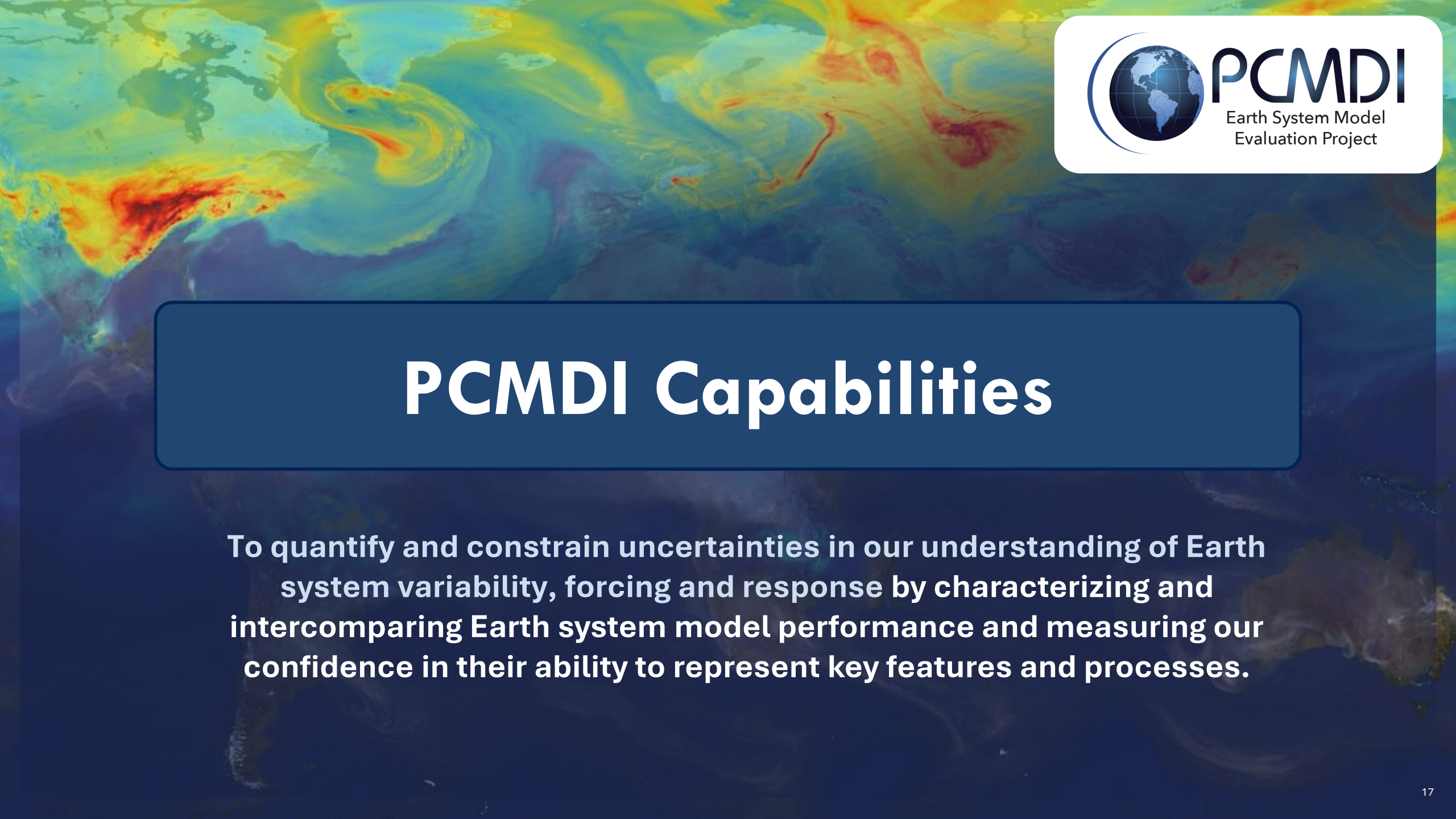
- WCRP Climate Sensitivity Assessment by Sherwood et al including Klein and Zelinka (2020): **Runner-up for *Science Magazine* Breakthrough of the Year in 2020**.
- Our science is featured **prominently in IPCC Assessment Reports (ARs)**.

Ultra-high resolution models open new possibilities for better simulating cloud feedbacks



- A new class of global high resolution “storm-resolving” models is being developed that do not require as many assumptions about small-scale processes that plague conventional models.
- In close collaboration with E3SM/SCREAM colleagues, we are currently exploring warming simulations with these models that explicitly resolve cloud-scale motions.
- We are investigating whether these have different cloud feedbacks and climate sensitivities than their coarse resolution predecessors, and why.

We are now examining clouds and their feedbacks in state-of-the-art models that better represent small-scale processes.



PCMDI
Earth System Model Evaluation Project

PCMDI Capabilities

To quantify and constrain uncertainties in our understanding of Earth system variability, forcing and response by characterizing and intercomparing Earth system model performance and measuring our confidence in their ability to represent key features and processes.

PCMDI Metrics Package (PMP)

PMP is:

A PCMDI-developed open-source Python package for consistent evaluation and benchmarking of climate models.

PMP does:

Assess model performance using diverse metrics

Ensure reproducibility with detailed provenance and version control of all codes, data, and operations

PMP provides metrics for:

Global climate	High-latitudes + Sea ice
Cloud feedbacks	Extratropical variability
Monsoonal systems	El Niño Southern Oscillation
Precipitation character	Madden-Julian Oscillation

Underway: Atmospheric Rivers, Stratosphere-Troposphere

Impacts:

Assess performance evolution across CMIP generations

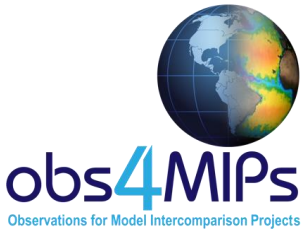
Provide objective goals for model development

Downloaded > 33K times and used for model evaluation by DOE and other agencies

E3SM Energy Exascale Earth System Model · NASA · NOAA · GFDL · National Institute of Meteorological Sciences · IPSL

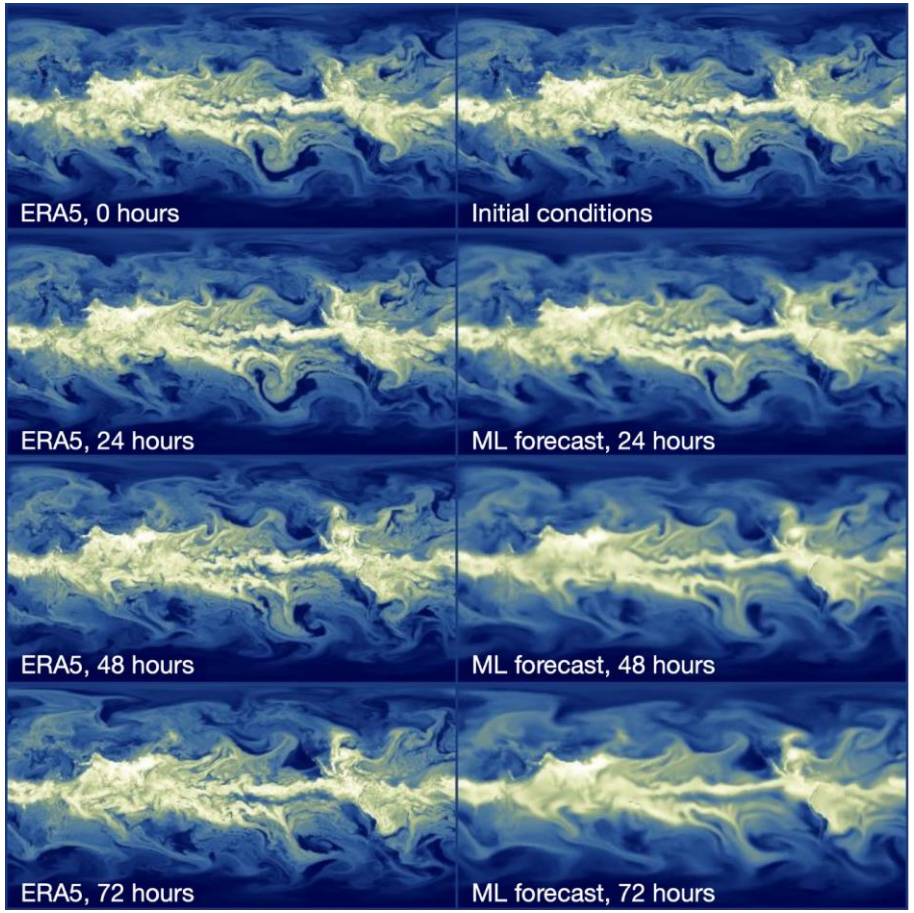
Other Capabilities and Support

- **Coordinated Model Evaluation Capabilities (CMEC):** Integrating community evaluation capabilities.
- **input4MIPs:** New community forcing datasets that support Earth system model experiments.
- **obs4MIPs:** Community standards to enable research-ready observational datasets.
- **CMOR:** An internationally employed tool for standardizing climate data to meet MIP requirements.
- **xCDAT:** A python package for streamlined climate data processing and analysis.



Collectively our software and data support efforts forge a tighter bond between observationalists, model diagnosticians, and model developers, accelerating the development and evaluation of Earth System Models

New Directions for Evaluation

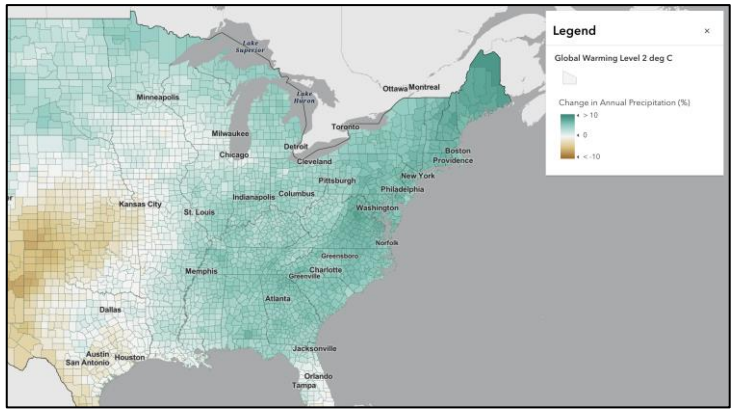


Evaluation of AI/ML-based Climate Emulators

- Process representation
- Relationships between fields
- Feature-based analysis
- Physical constraints

Evaluation of Decision-Relevant Climate Data

- Understand differences between production methods
- Focus on use-inspired metrics
- Develop evaluation standards
- Codify expert guidance



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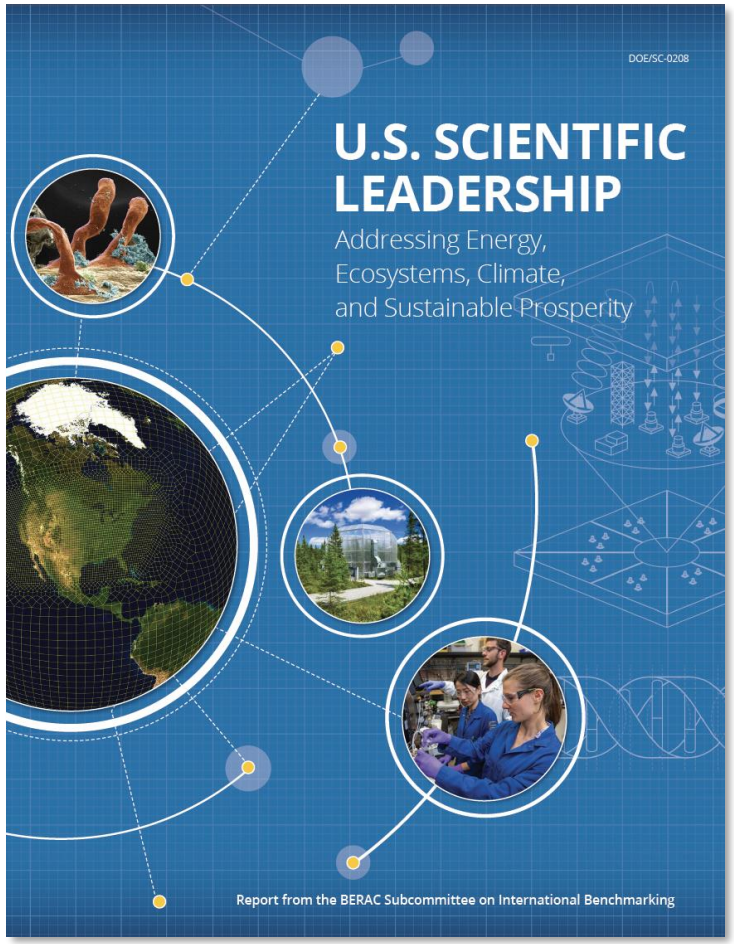
PCMDI
Earth System Model Evaluation Project

PCMDI Leadership

To quantify and constrain uncertainties in our understanding of Earth system variability, forcing and response by coordinating, facilitating, and enabling climate research to leverage the latest model- and observational-based insights.

DOE BERAC Committee Recognize and Recommend



CMIP—Coupled Model Intercomparison Project

The Coupled Model Intercomparison Project (CMIP) is the most prominent and significant international model intercomparison project devised to date. It has achieved far-reaching success in the international climate science community thanks to support and leadership from BER.

Takeaway

BER support of and leadership in CMIP has been vital to the project's far-reaching success in the international climate science community.

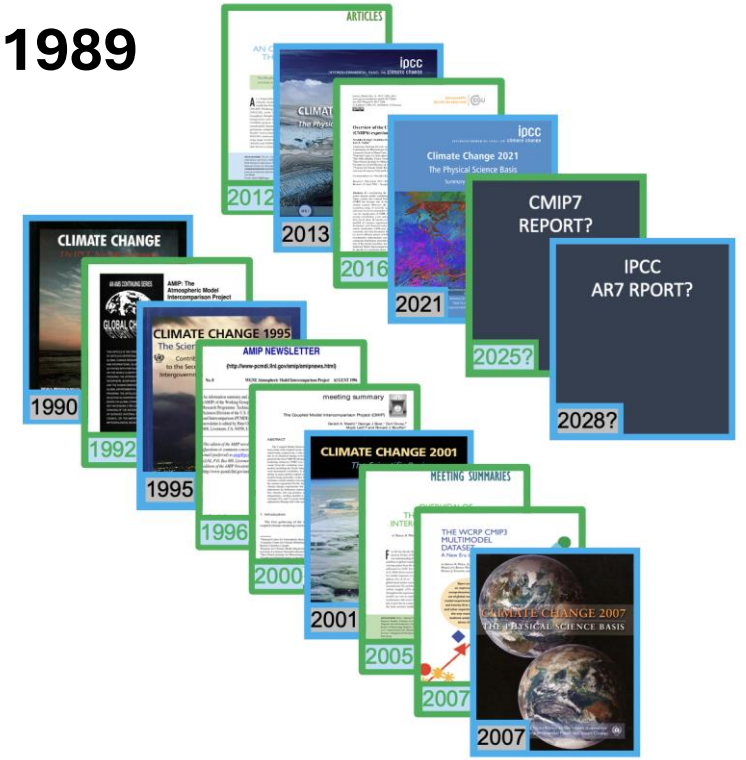
Chapter 5

Key Findings and Recommendations

KF5.2 BER has demonstrated international leadership in developing and interpreting climate model intercomparisons through the DOE Program for Climate Model Diagnosis and Intercomparison (PCMDI) and was a leading contributor to research earning the 2007 Nobel Peace Prize awarded to the Intergovernmental Panel on Climate Change and former U.S. Vice President Al Gore.

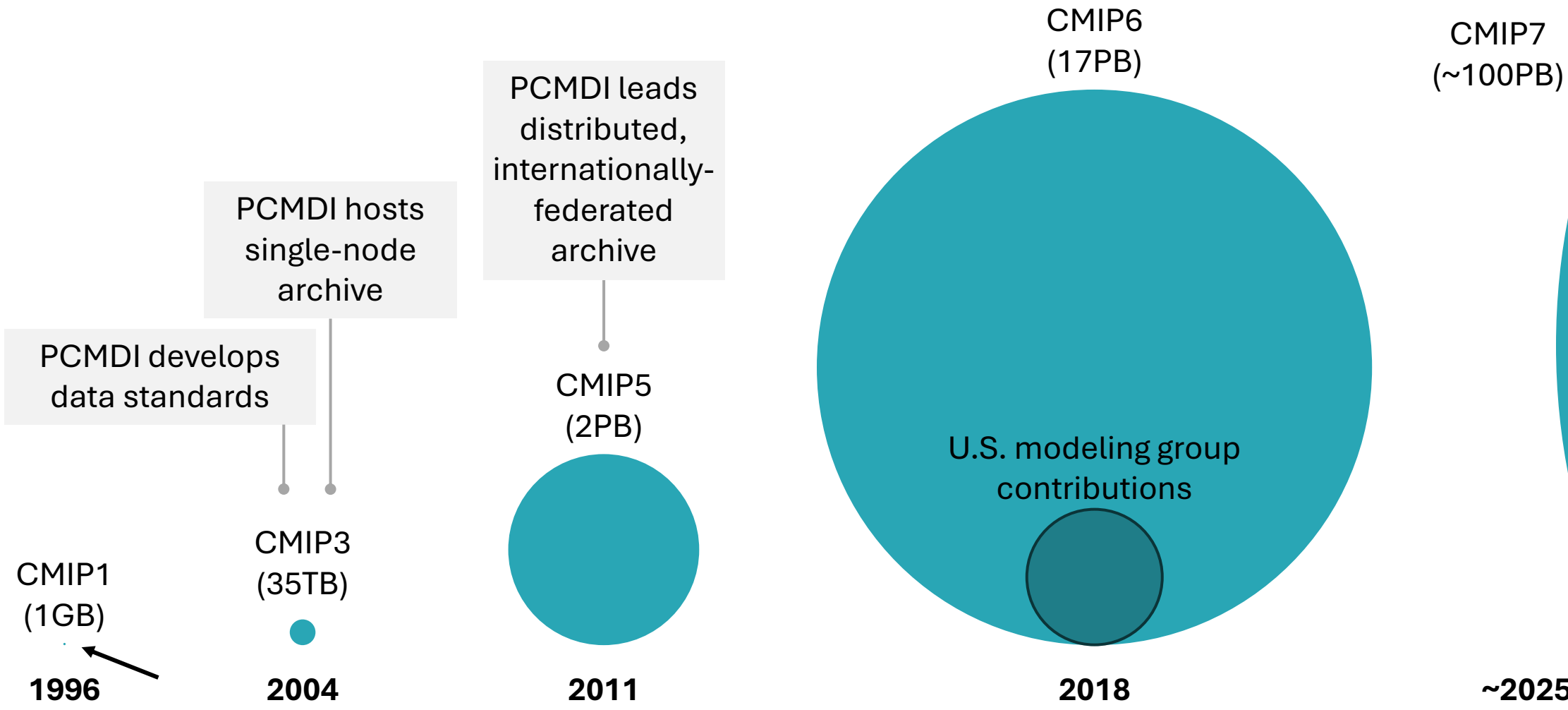
PCMDI Leadership

- **Leaders of Model Intercomparison Projects (MIPs) since 1989**
- **DOE-BER PCMDI funded scientists are**
  - Founding Members and Chairs of Atmospheric Model Intercomparison Project (AMIP) Panel (1990-2001)
  - Founding Members - WCRP Coupled Model Intercomparison Project (CMIP) Panel (1995-)
  - Founding Members and Co-chairs - World Climate Research Program (WCRP) Infrastructure Panel (2013-)
  - Co-leads/Members - CMIP Task Teams for Climate Forcings and Model Benchmarking
  - Invited Lead Authors of all six Intergovernmental Panel on Climate Change (IPCC) Assessment Reports (1990-2021)

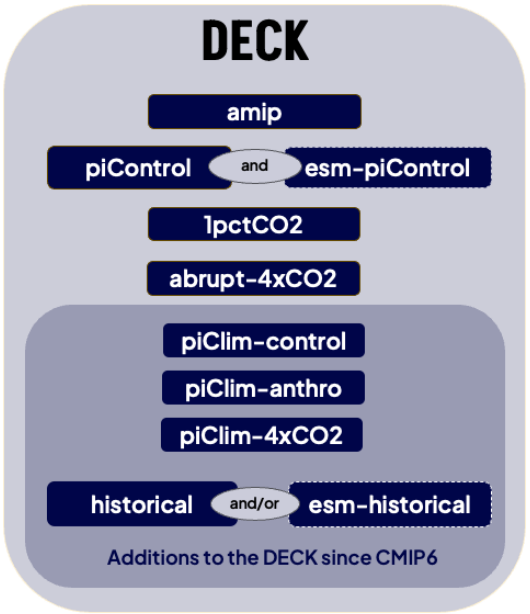


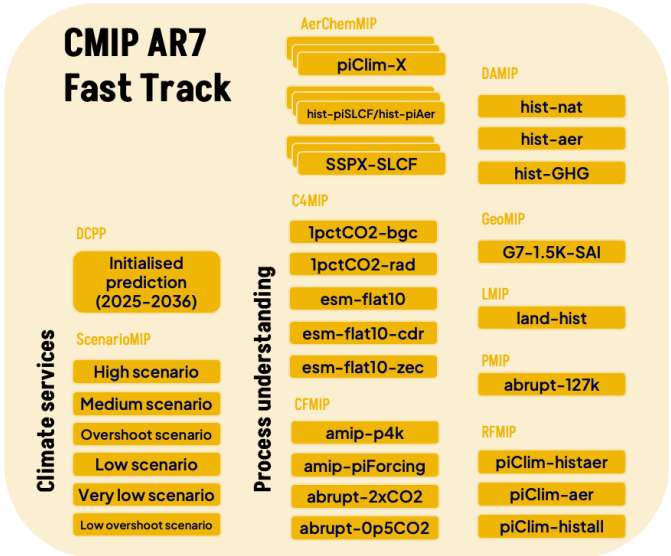
DOE BER Advisory Committee 2022 recognized PCMDI's CMIP leadership and support benchmark achievement

MIP Science Expansion Continues



CMIP7 Opportunities





- CMIP7 starts with AR7 Fast Track ~2025-26
  - CMIP DECK, 8 experiments model evaluation
  - +MIPs plus ~50 experiments, model sensitivity (AerChemMIP, C4MIP, CFMIP, LMIP, GeoMIP, PMIP, RFMIP), model forcing responses (C4MIP, DAMIP, ScenarioMIP)

- **Science:** Forcing responses, extremes, carbon cycle, tipping points

- **Engagement opportunities:** MIPs, data request community consultation (atmosphere: Mark; ocean: Paul D; WIP: Paul D, Karl), forcings workshop, model documentation community consultation, model benchmarking – rapid evaluation framework (Jiwoo Lee); obs4MIPs (Peter Gleckler), …

obs4MIPs
Observations for Model Intercomparison Projects

input4MIPs
input datasets for Model Intercomparison Projects

Understanding Decision-Relevant Regional Climate Data Products Workshop

November 14-16, 2023 in Berkeley, California

A meeting of scientists from DOE and DOD/SERDP, together with researchers, data producers, end-users and agency representatives to understand the state of the nation's decision-relevant regional climate datasets and projections.

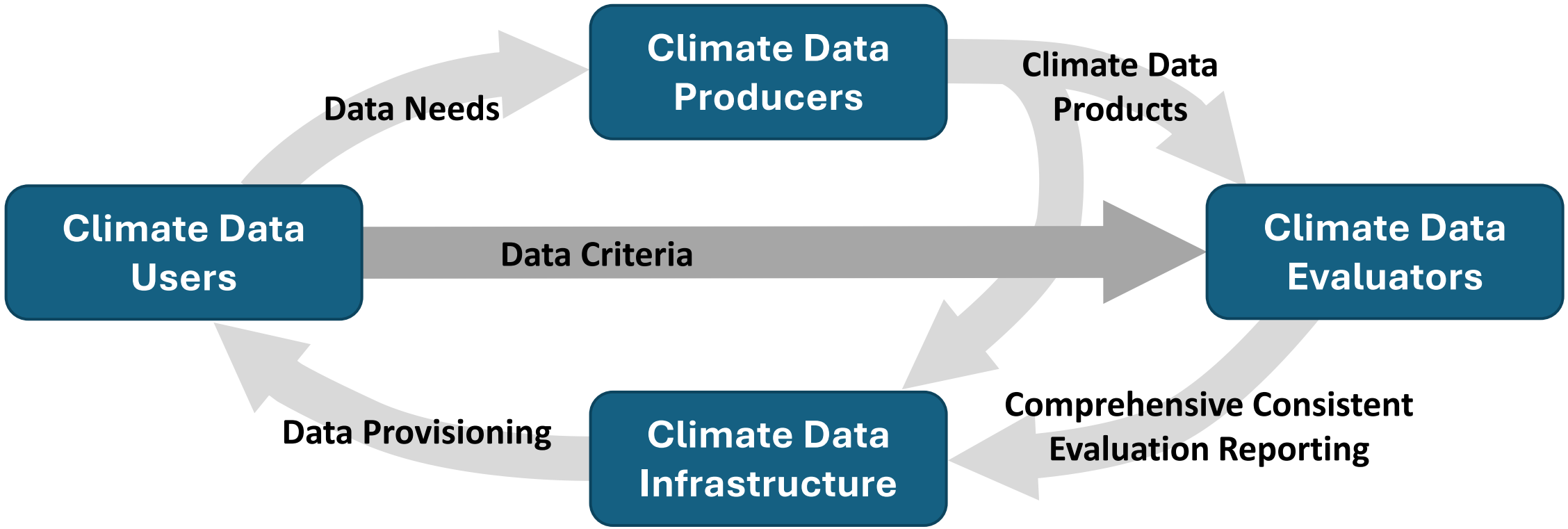
All operational approaches considered, including statistical downscaling, dynamical downscaling, hybrid downscaling, regionally-refined global modeling and AI/ML based methods.

Workshop scope: How to characterize the strengths and weaknesses of decision-relevant climate data products and build bridges between data producers, data analysts and data users.

United States Global Change Research Program

Understanding Decision-Relevant Regional Climate Data Products: Building a Community of Practice

We are working towards building a community of practice around decision relevant climate data, levering our expertise in common data and evaluation standards.



PCMDI Overview

- PCMDI is among the most recognized names in the climate science community, with a long and established history tackling the science of climate change.
- PCMDI is a hub for climate research in the DOE and beyond. The project has extensive expertise with data standards, model evaluation, and experiment design. PCMDI's efforts have been responsible for accelerating climate research around the world.
- PCMDI are leaders in the global climate research community, with contributions to the Intergovernmental Panel on Climate Change since its inception.

PCMDI Science Overview

- We have improved quantification, understanding, and constraints on cloud feedbacks and climate sensitivity and are extending this to ultra high resolution models.
- We have identified human fingerprints across the climate system, and are disentangling forced and unforced climate signals for better interpretation of our past climate and its implications for the future.
- We have established the importance of warming patterns in modulating radiative feedbacks and developed quantification tools for it, and are exploring causes, consequences, and constraints on it.

Project Overview

Our Goal

To quantify and reduce uncertainties in Earth system variability, forcing and response

Relevant scientific expertise

- Cloud processes and feedbacks
- Precipitation processes
- Detection and attribution
- Radiation and remote sensing
- Atmospheric and climate dynamics
- Ocean and marine science
- Climate prediction

Relevant technical expertise

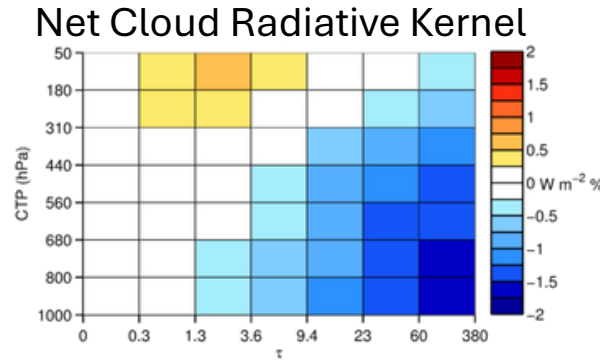
- Big data management
- Statistical techniques
- Machine learning and data science
- Emergent constraints
- Radiative feedback diagnosis
- Climate forcing development
- Experimental design and protocol
- Model evaluation and benchmarking
- International model intercomparison leadership

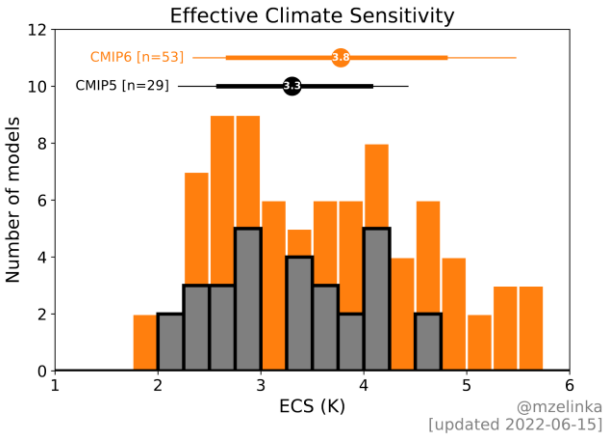
Open Science: Supporting the Broader Community

- Approximate Partial Radiative Perturbation Code
- Cloud Radiative Kernels
- Disentanglement Software
- Forcing, Feedback, and ECS values from CMIP5/6
- Green's Functions
- Meteorological Cloud Radiative Kernels
- MSU Atmospheric Temperature Emulator
- Radiative Feedback Quantification Codes
- International Leadership codes…

jupyter

zenodo





We are committed to open science and facilitating research from the broader scientific community.