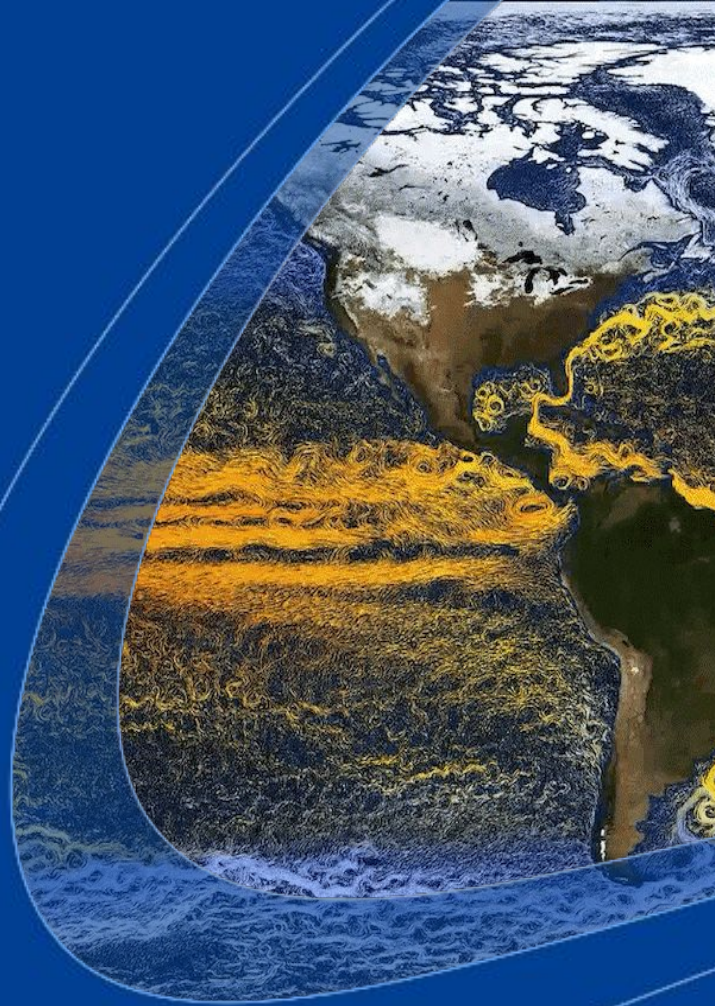
NCAR
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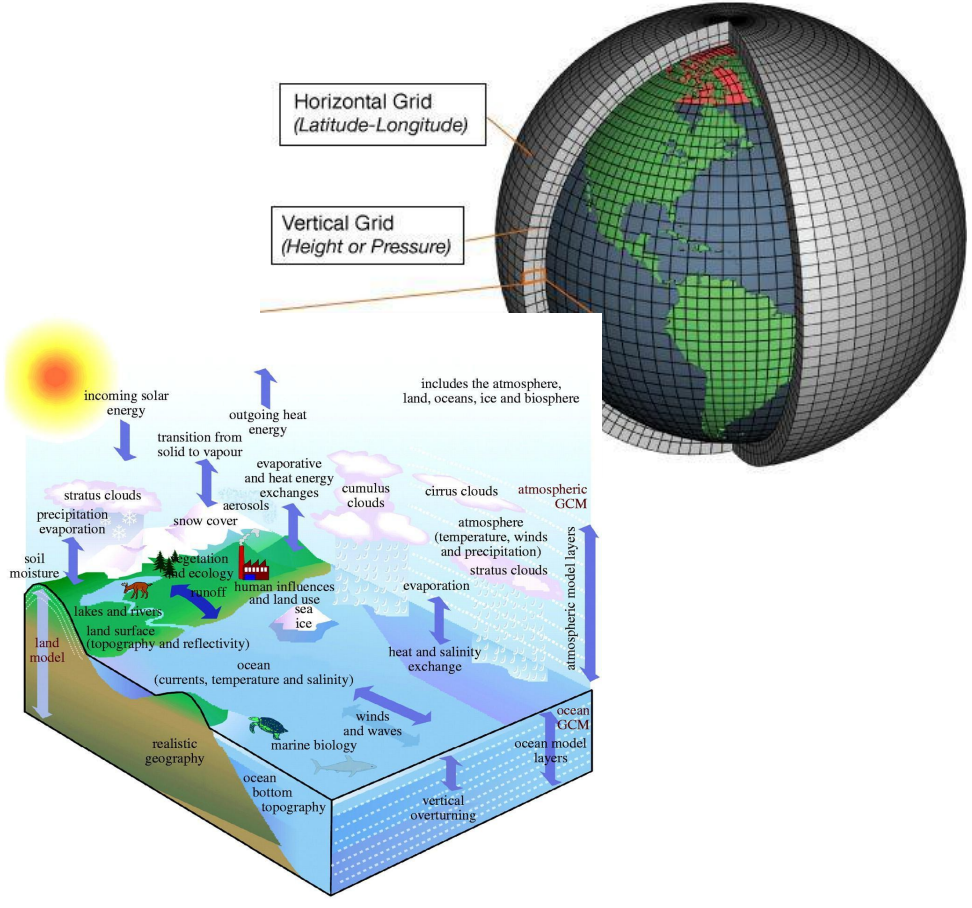
Introduction to the Community Earth System Model (CESM)

David Lawrence
CESM Chief Scientist

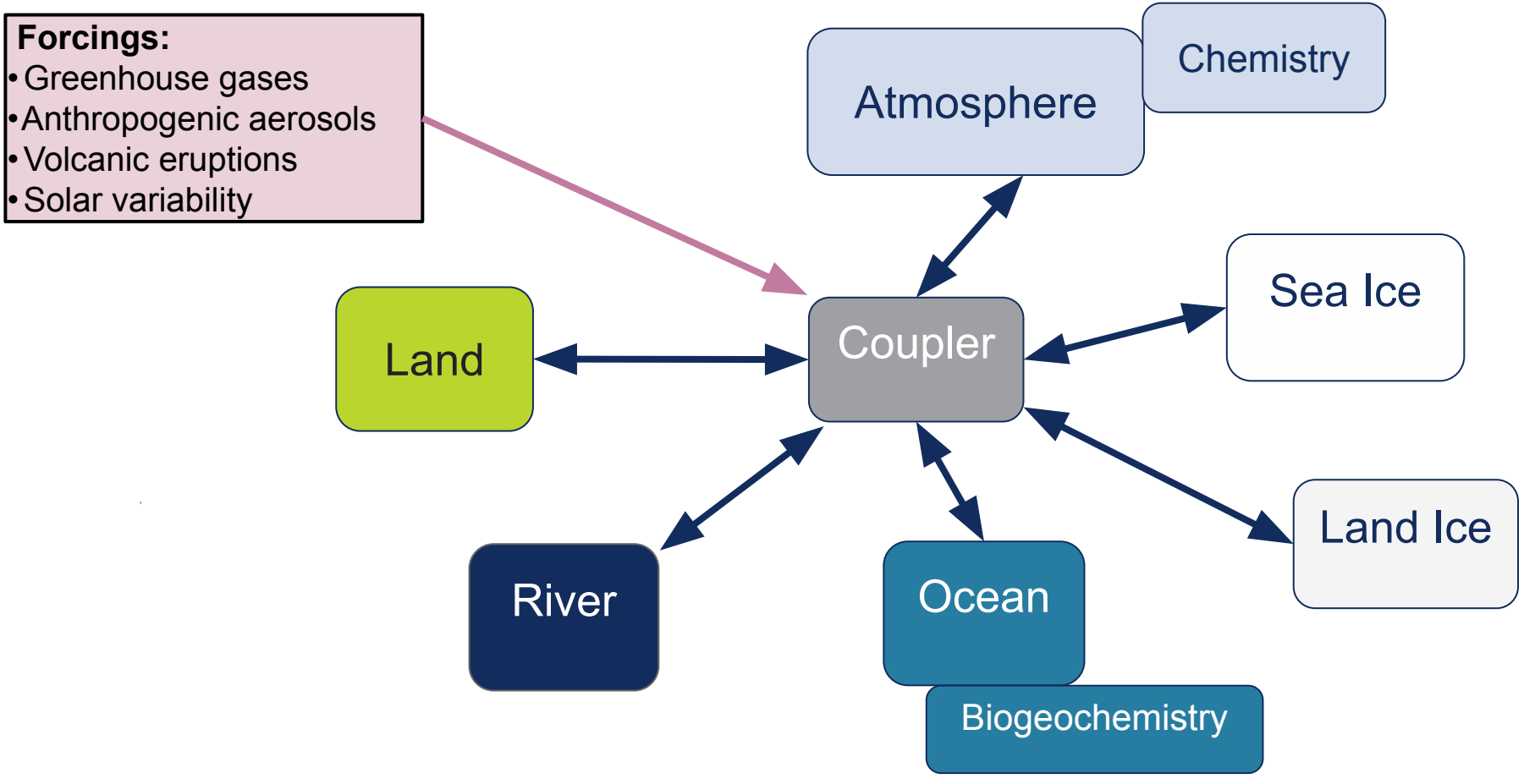


Global Earth System Models

- The models use physical equations to simulate key fields and processes in the atmosphere, ocean, land, sea-ice, land-ice, …
- Processes that remain below the grid resolution need to be parameterized
- Build on our understanding of processes from observations and highly-detailed models (e.g., process models, large eddy simulations)



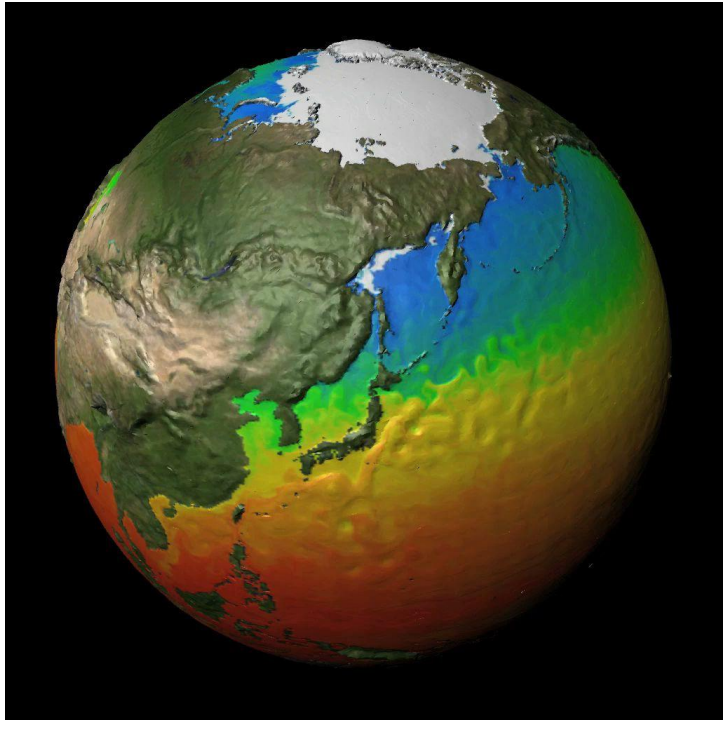
Structure of a fully coupled Earth System Model



Global Earth System Models

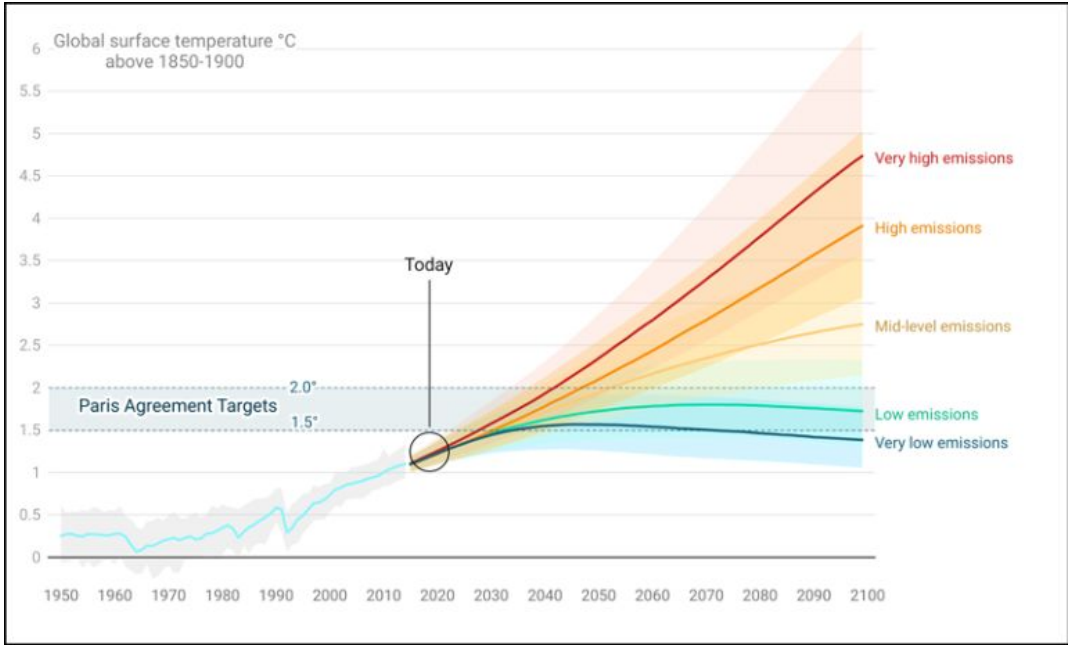
Many purposes including:

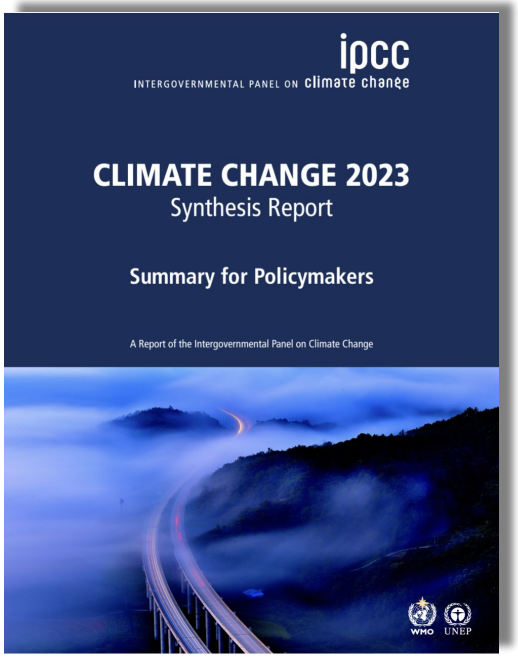
- Scientific and mechanistic understanding of past observed events and changes
- Studying recent past, present, and future (projections) climate changes and their impacts
- Understanding climate variability
- Subseasonal-to-multidecadal Earth system predictions
- Providing actionable, societally-relevant information



Small and Scheitlin

Output from Earth System Models is key basis for IPCC reports



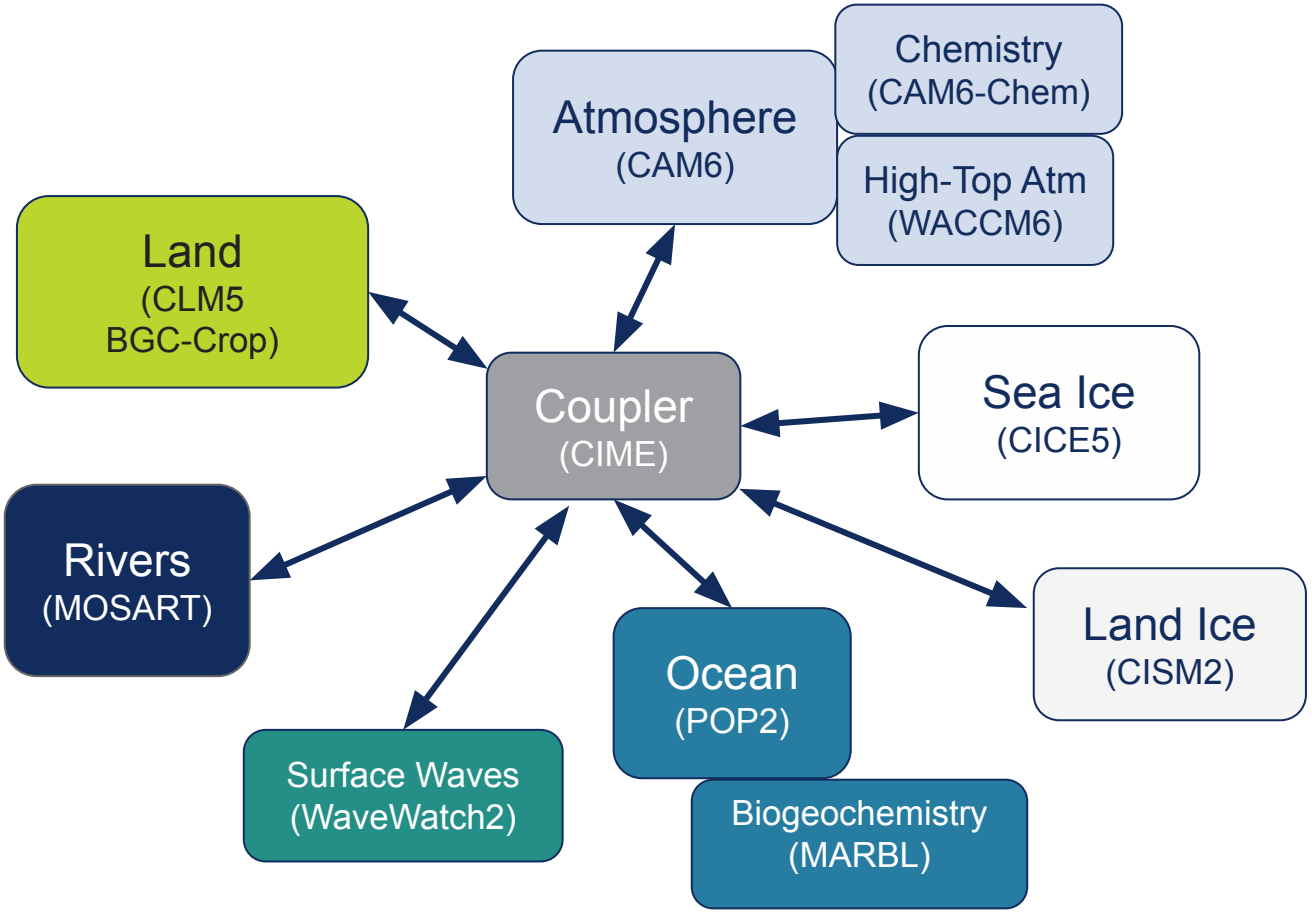


IPCC, AR6 Report

Community Earth System Model (CESM2)



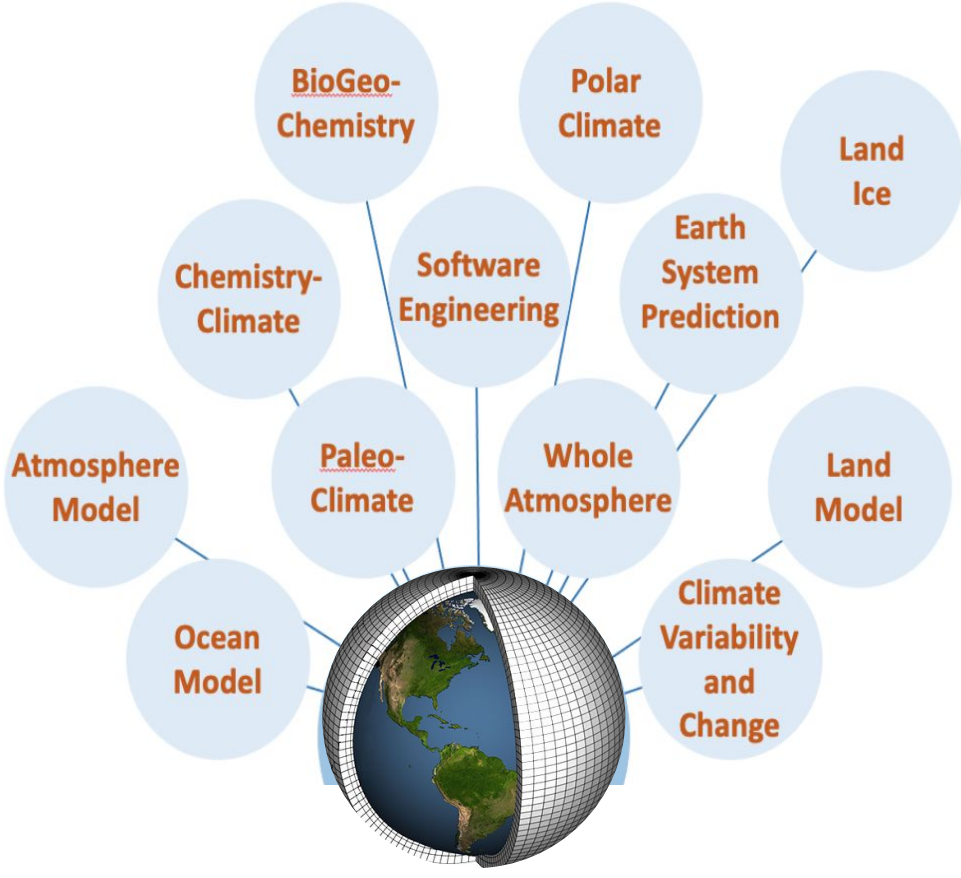
Model configuration used for simulations submitted to the Coupled Model Intercomparison Project (CMIP6) and many other community simulations (e.g., CESM2 Large Ensemble)



Community Earth System Model (CESM)

NCAR | CESM
Community Earth System Model

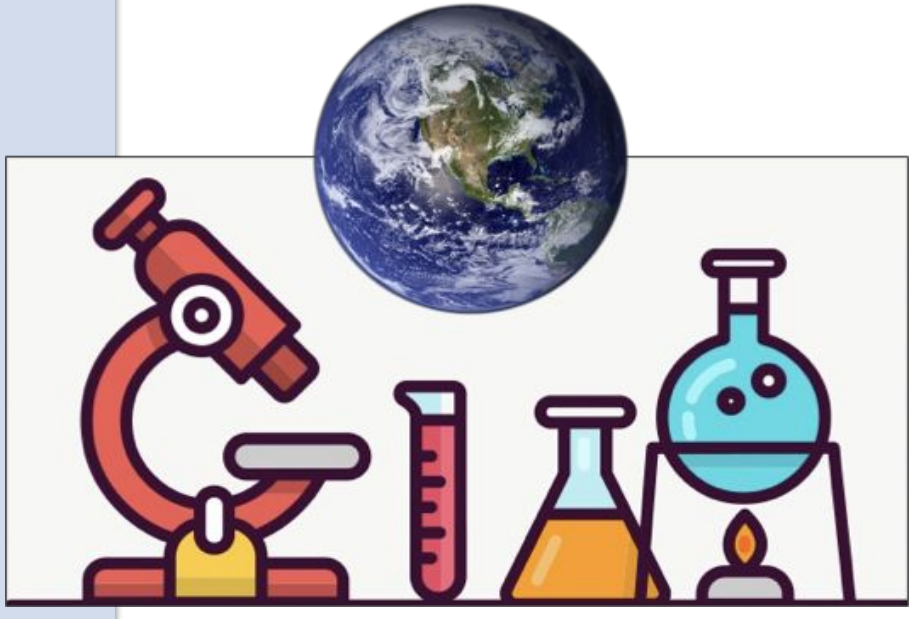
- One of world's leading models for studies of climate change and climate variability (CMIP, IPCC)
- Represents 30+ years of development
- A true community model (development & support)
- Community participation through working groups (2000+ researchers)
- Widely used, e.g., 450+ talks using CESM at AGU 2024
- 4.5 million lines of Fortran (!) code, >1000 geophysical variables



CESM is a virtual laboratory for the research community

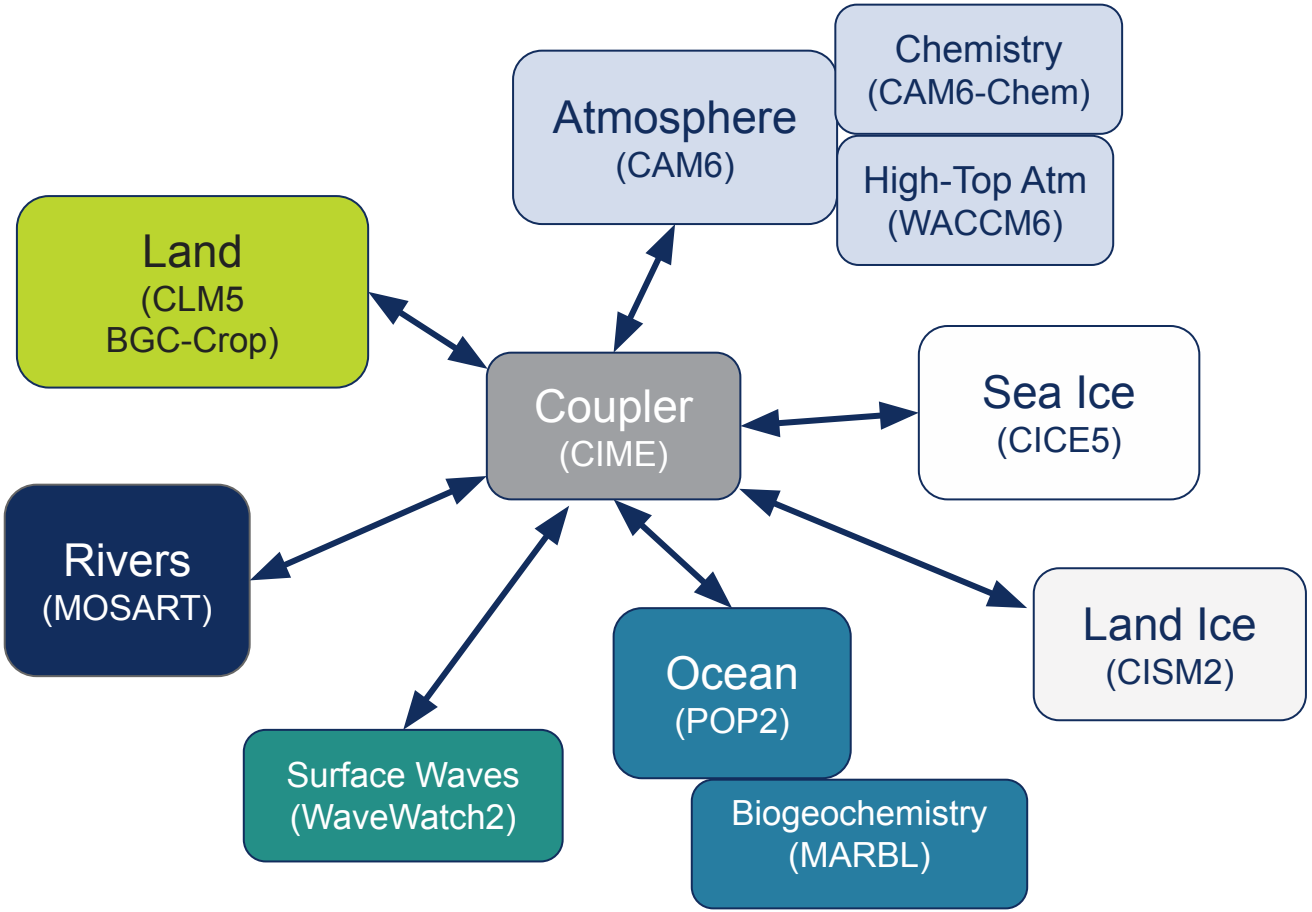
Virtual laboratory to study

- Earth system variability and change
- Air quality
- Biogeochemical cycles
- Earth system predictability (S2S, S2D)
- Weather from local to global scales
- Process understanding
- Land-atmosphere and ocean-atmosphere interactions
- Ice sheet - climate interactions
- Hydrology and ecology
- Solar functioning and space weather
- ...



CESM supports a range of climate science research through a single model code base



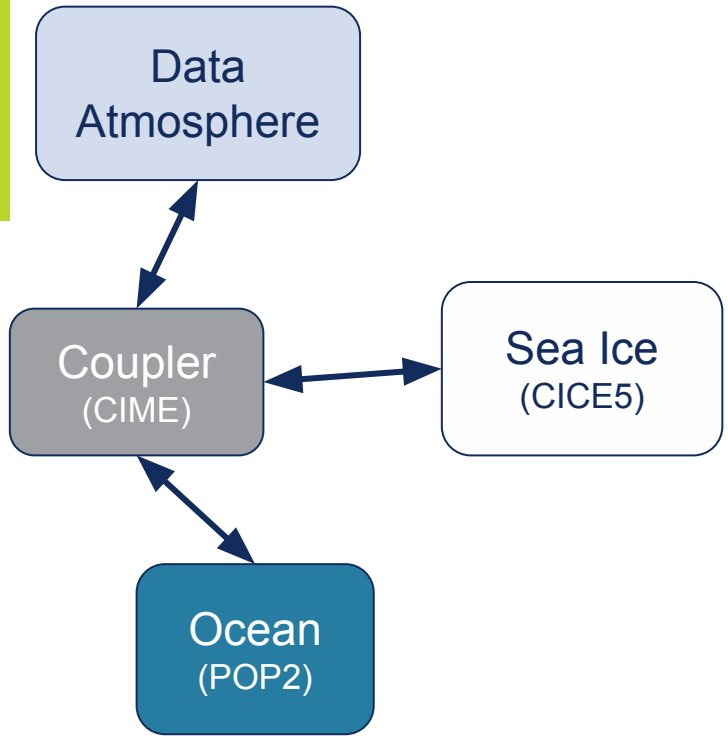


CESM supports a range of climate science research through a single model code base



For example, you can turn on and turn off different components and replace them with a Data model

T, P, Solar Radiation, Longwave Radiation, Humidity, Wind, CO2, etc. from observations (reanalysis)

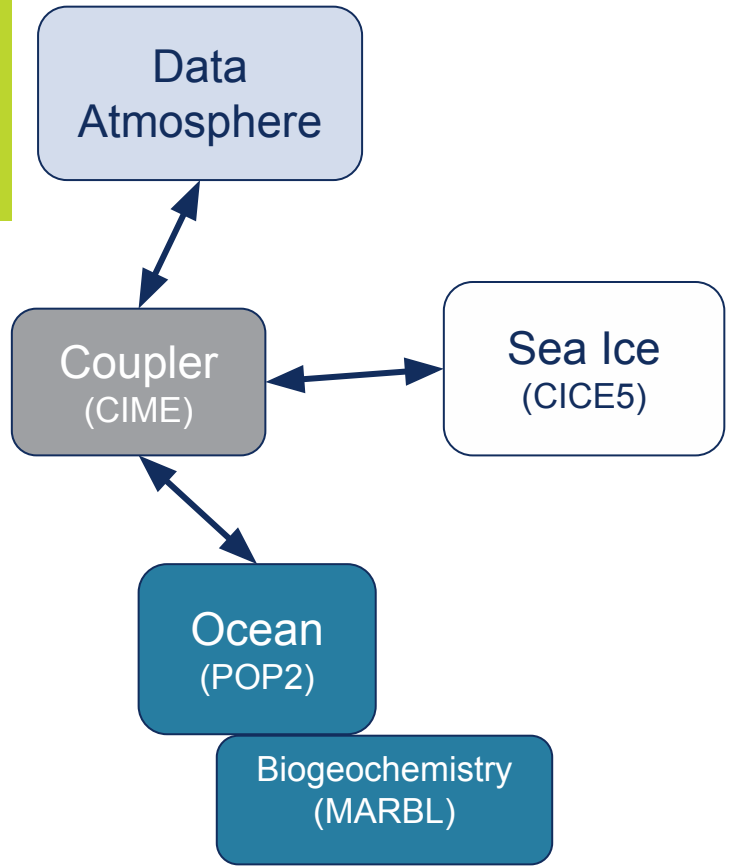


CESM supports a range of climate science research through a single model code base



For example, you can turn on and turn off different components and replace them with a Data model

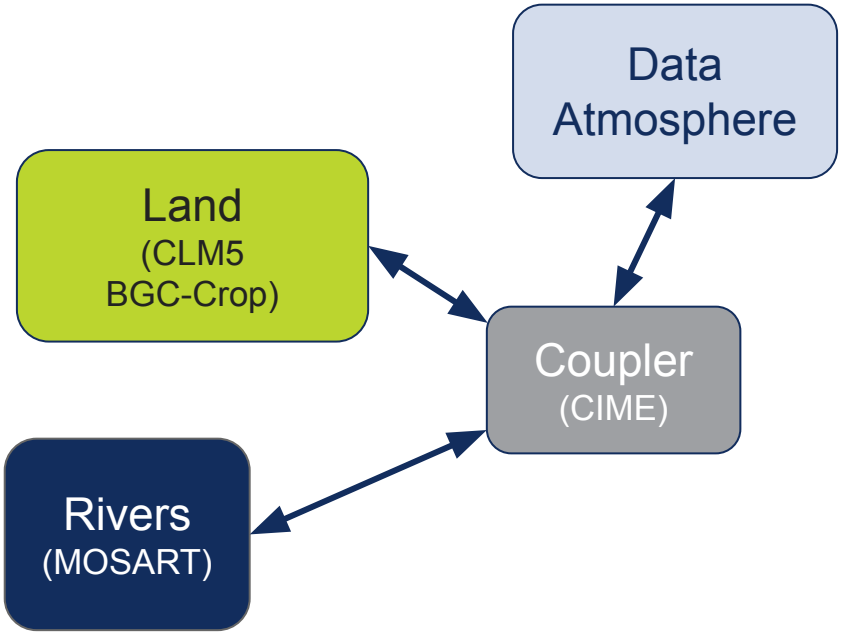
T, P, Solar Radiation, Longwave Radiation, Humidity, Wind, CO2, etc. from observations (reanalysis)



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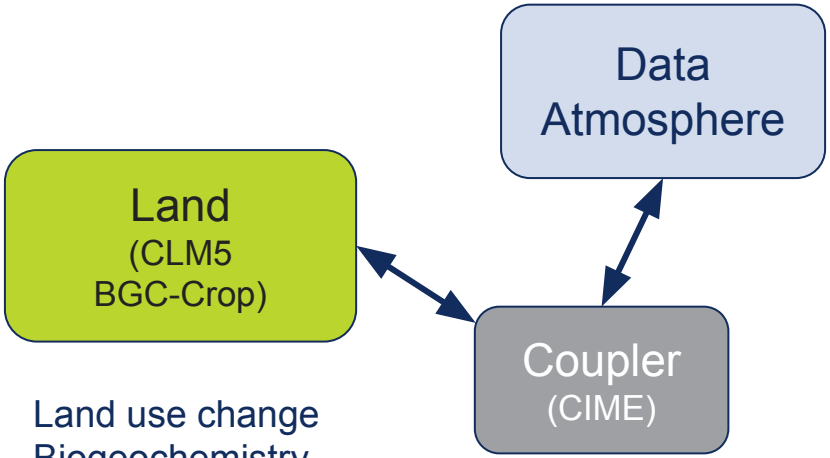
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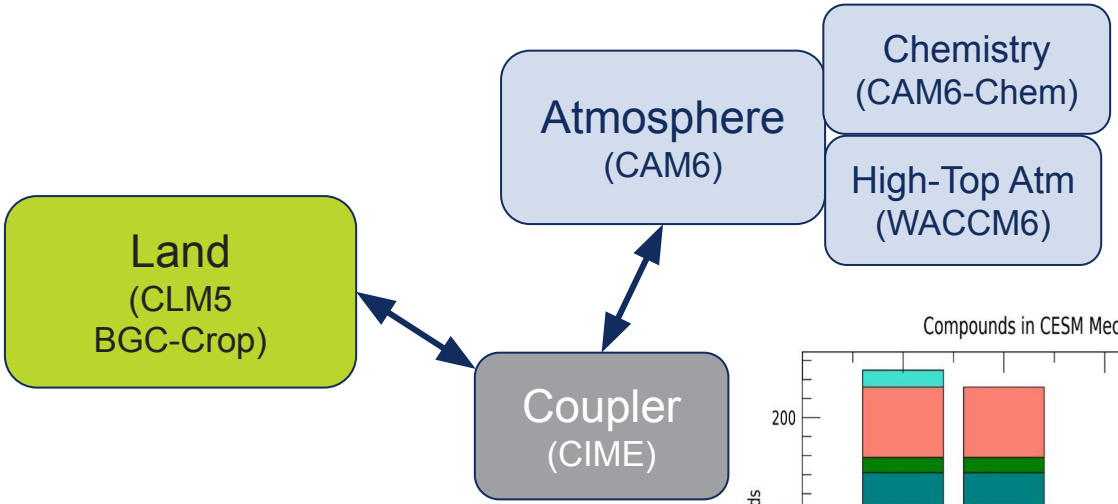
And, within each component model, there are many choices you can make about parameterizations, complexity levels, etc.

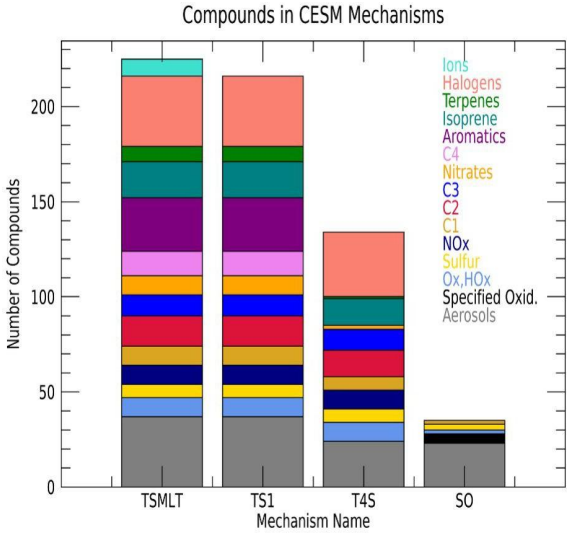


- Land use change
- Biogeochemistry
- Crops
- Prescribed vegetation
- Ozone damage
- Methane emissions
- # Soil layers
- No anthro
- …

CESM supports a range of Earth system science research through a single model code base







Earth System models and data can be a tool in your research toolbox

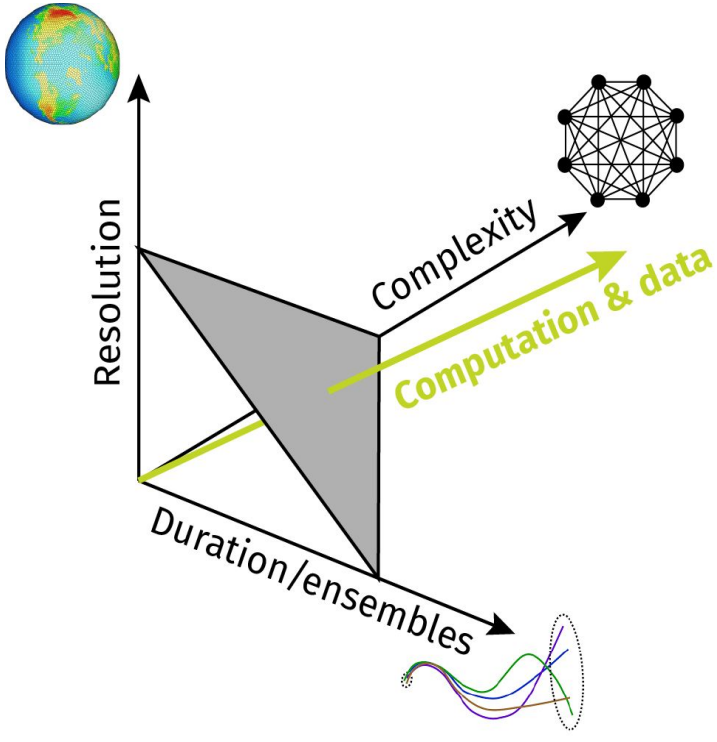
- **This week, you'll learn about**
  - the land component within CESM and the science behind it
  - how to setup, run, and make simple modifications to CLM
  - some ways that CESM and CLM are being used to address broad range of science questions

- **But, that's just the beginning …**
  - learning how to usefully apply ESMs and ESM data to answer research questions never ends
  - advice: be creative, acknowledge that there will be missteps, have fun!

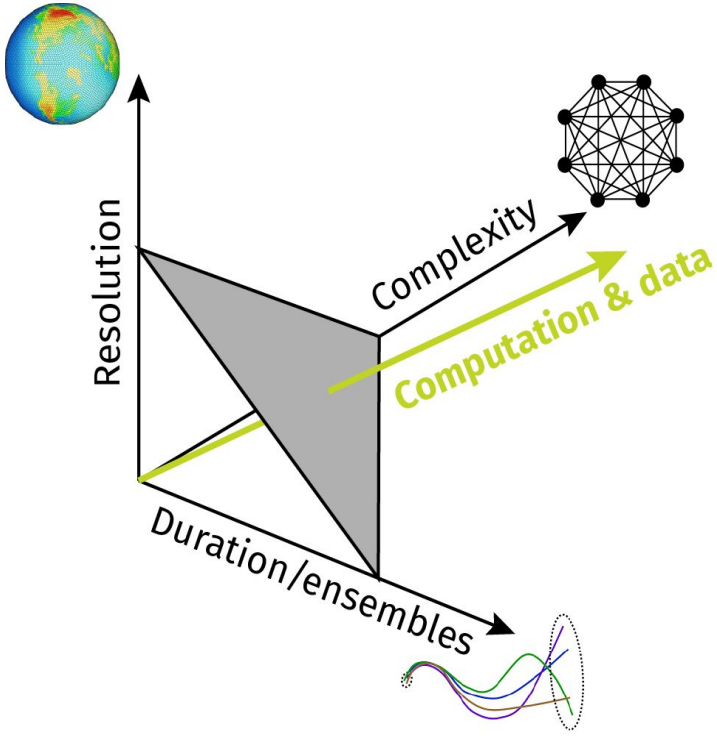
Earth System Modelling is hard!



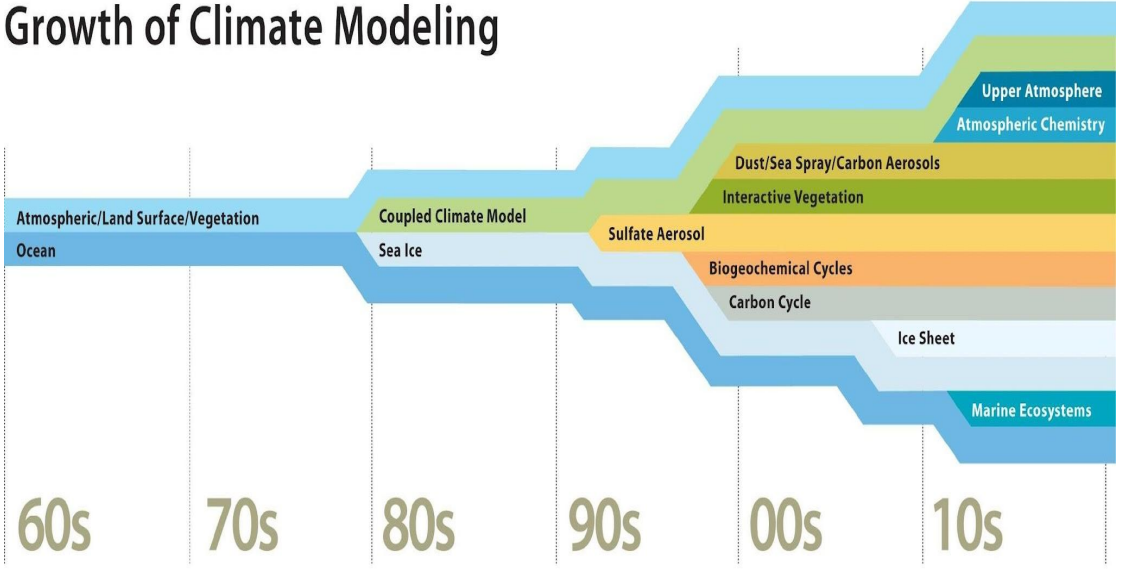
Different research questions require different considerations



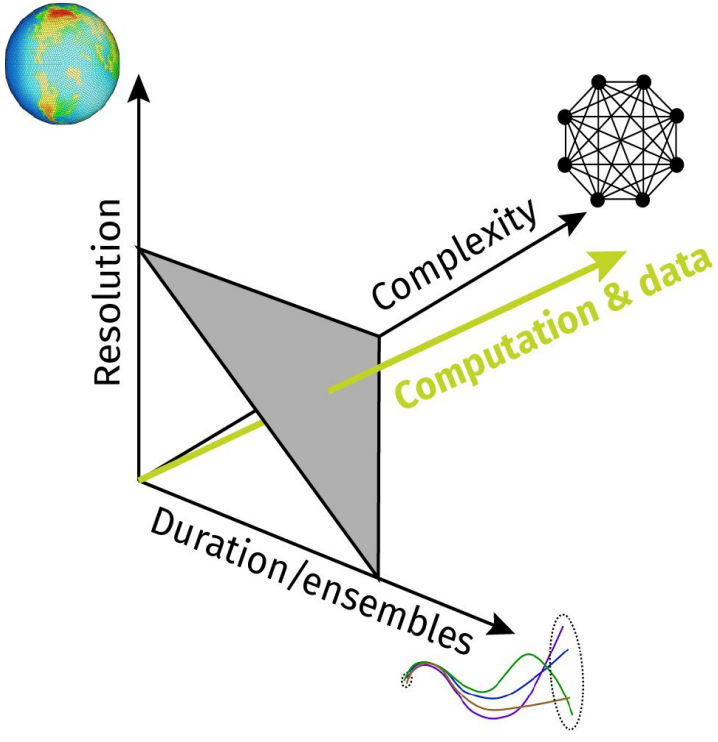
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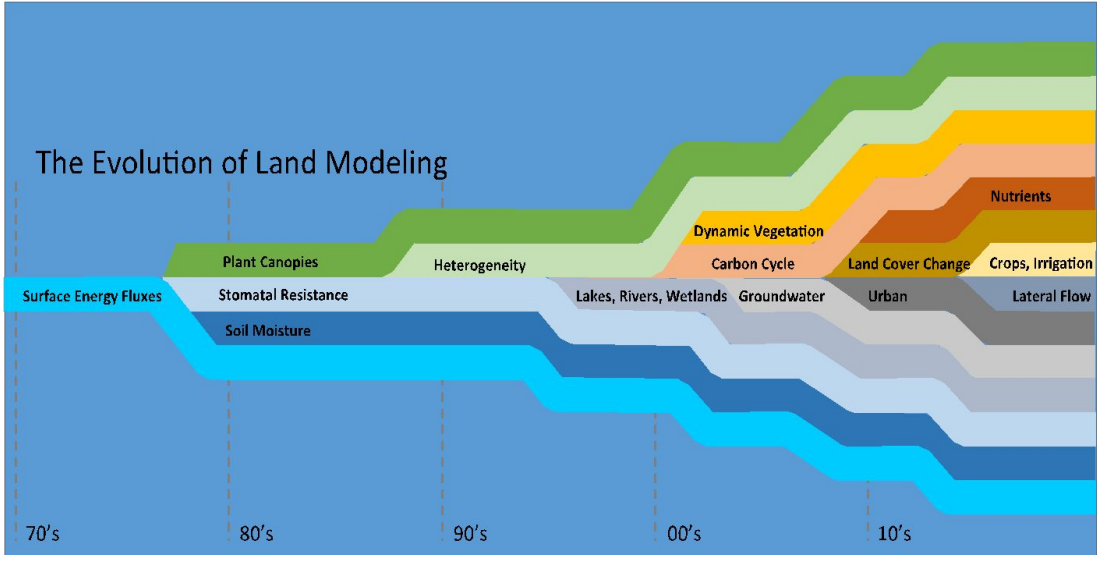
Complexity



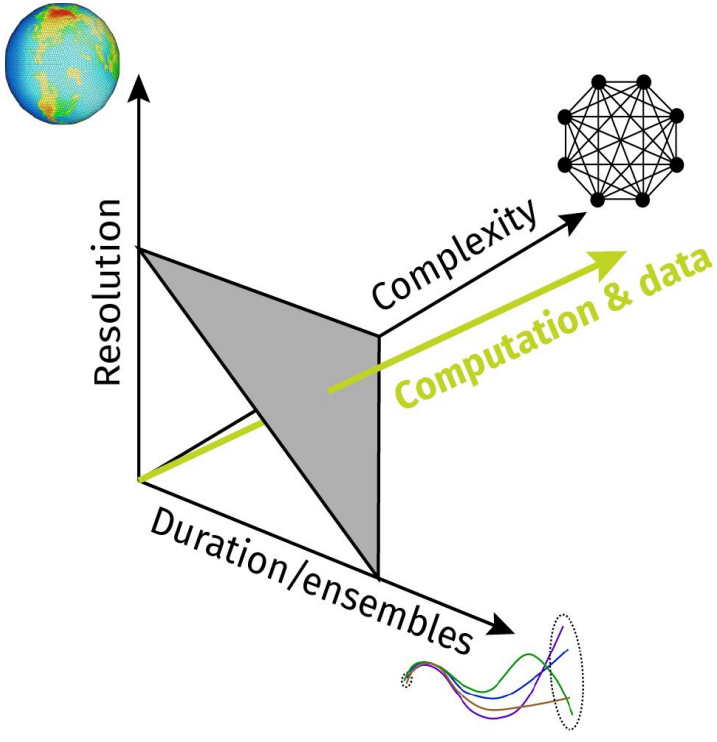
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Complexity



Different research questions require different considerations

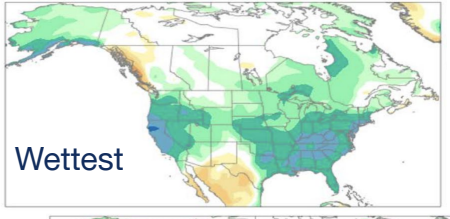


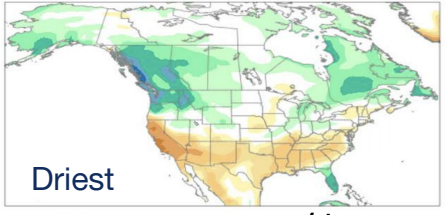
Large ensembles
climate change uncertainty

Internal vs Forced

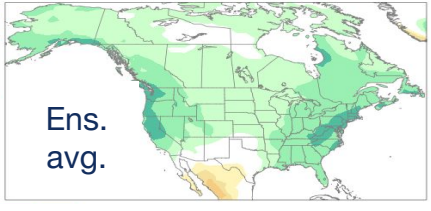


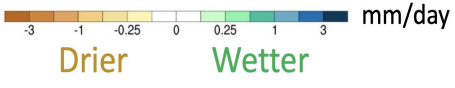




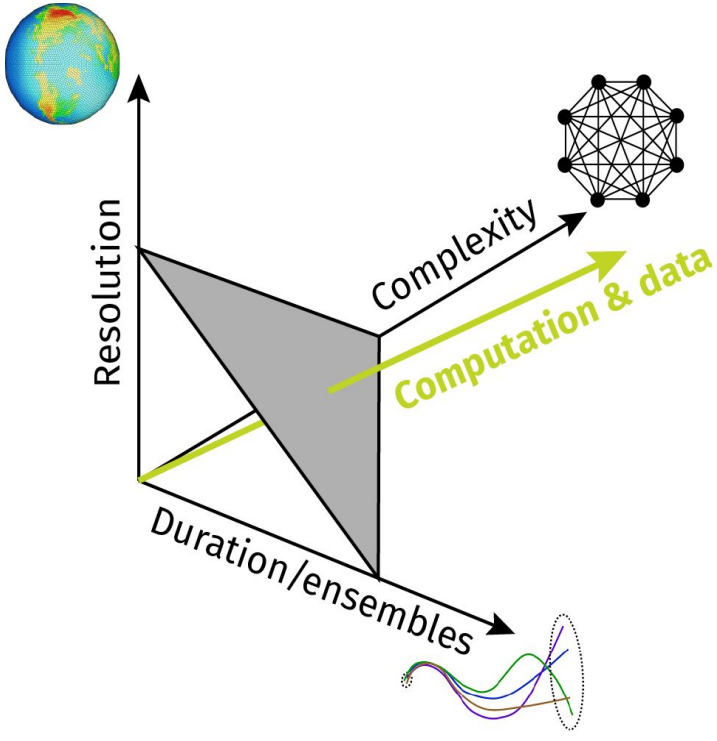


Winter Precipitation Trend
(2010-2060)

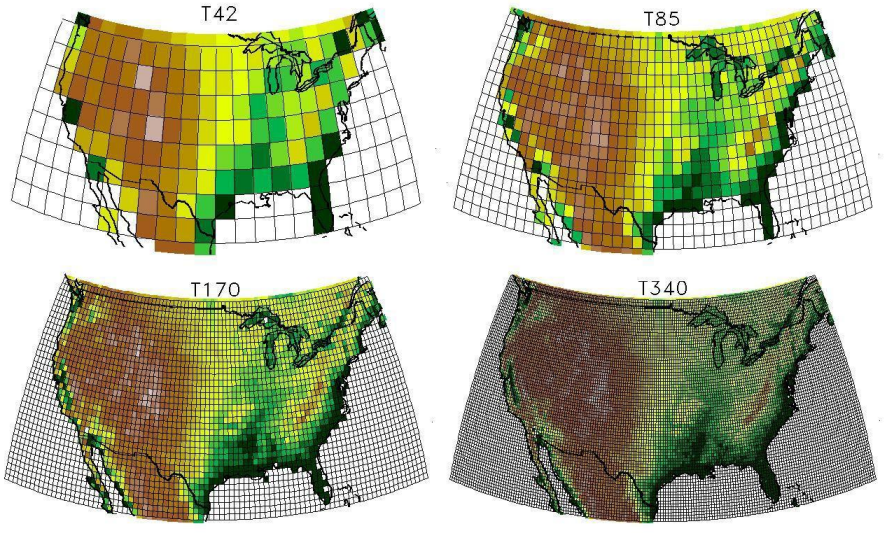




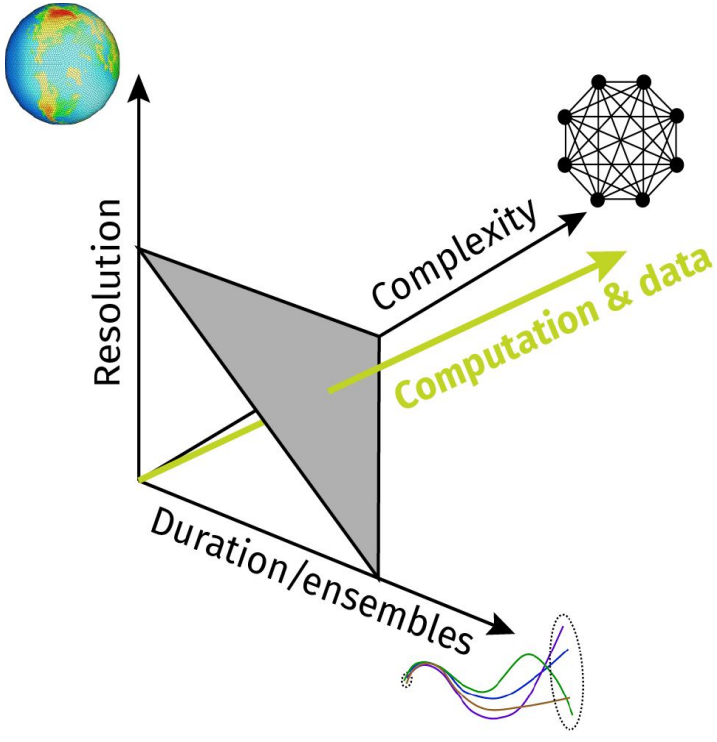
Different research questions require different considerations



Resolution

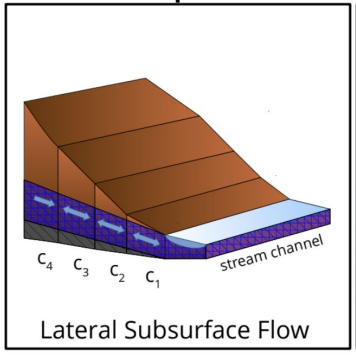


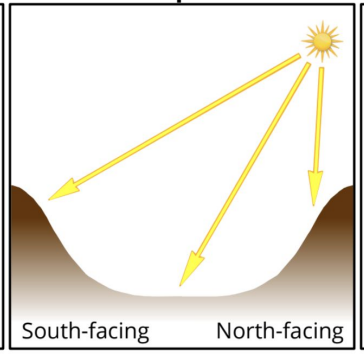
Different research questions require different considerations

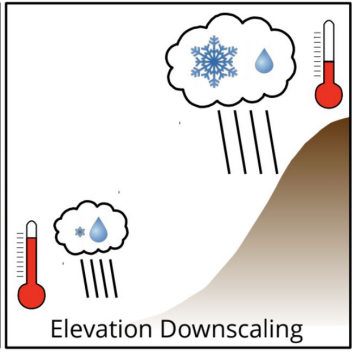


Resolution

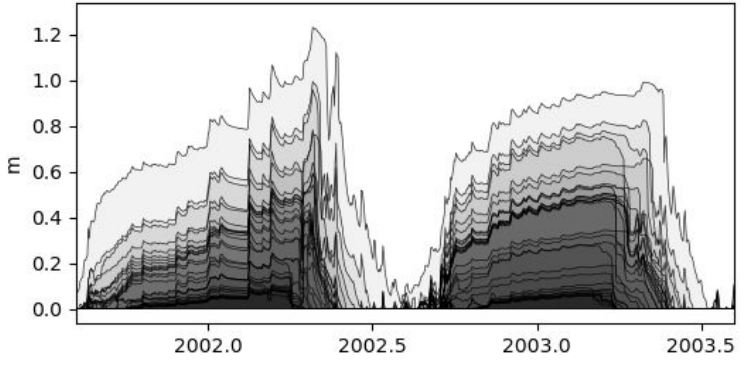
Representative Hillsope Model in CLM







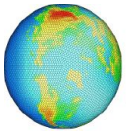
Snow depth for 32 hillslope columns



Providing CESM Data for the Community
Including for AI Training

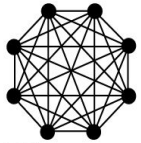


CESM Simulation Data
20+ PBs
1000's of geophysical variables at hourly, daily, monthly timescales



MESACLIP
Citations: >500
New

DYAMOND
New



CMIP5, CMIP6
Citations: Many thousands

Large Ensembles
(CESM1, CESM2) Citations: >3200

Last Millennium Ensemble
Citations: >600

Perturbed Parameter Ensembles
(CAM, CLM)
Citations: >20 citations
New

GDEX

S2S, Seasonal to Multi-Year, and Decadal reforecasts
Citations: >350

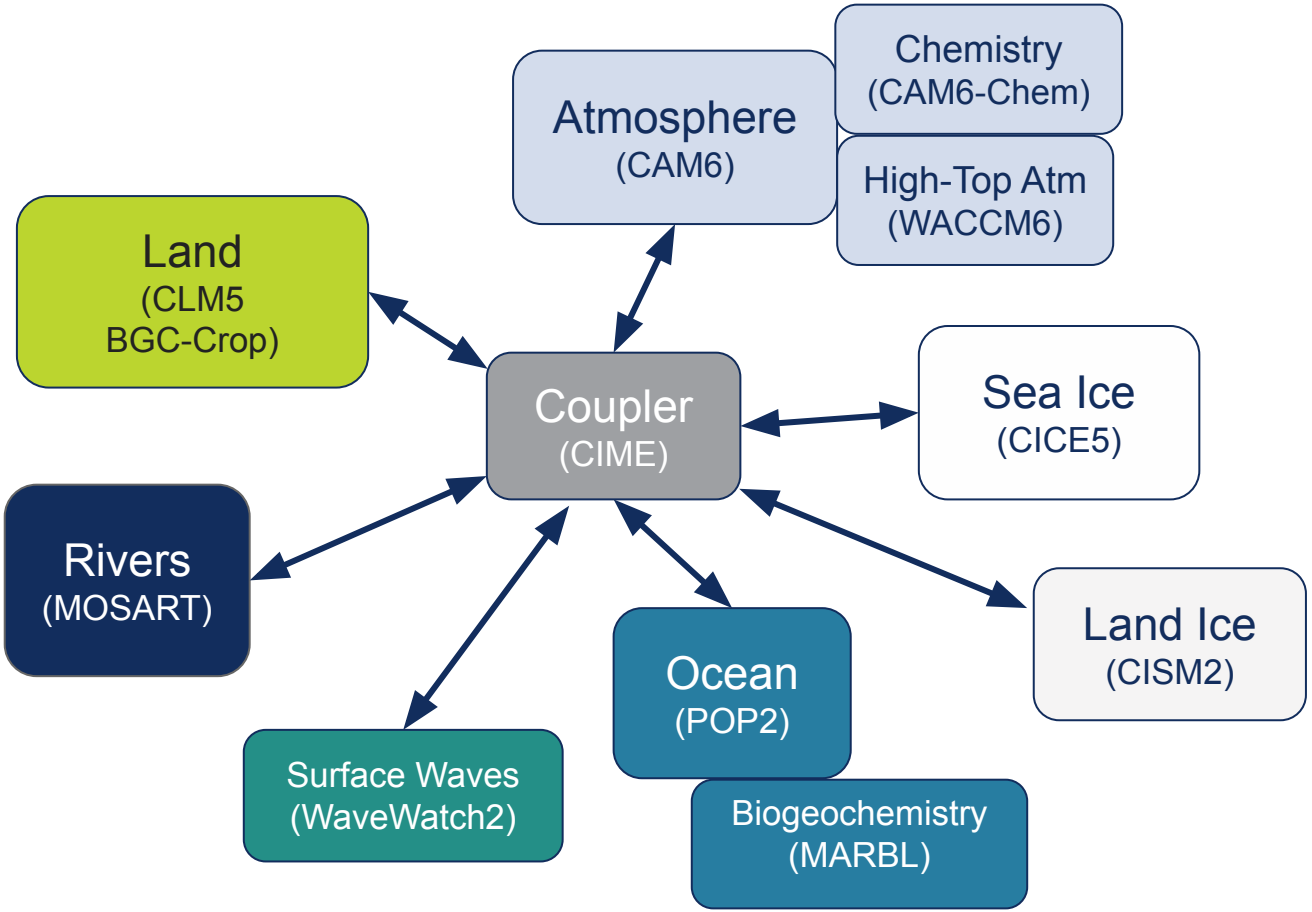
*The datasets here are a non-comprehensive subset of published simulation datasets

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Community Earth System Model (CESM2)



Model configuration used for simulations submitted to the Coupled Model Intercomparison Project (CMIP6) and many other community simulations (e.g., CESM2 Large Ensemble)

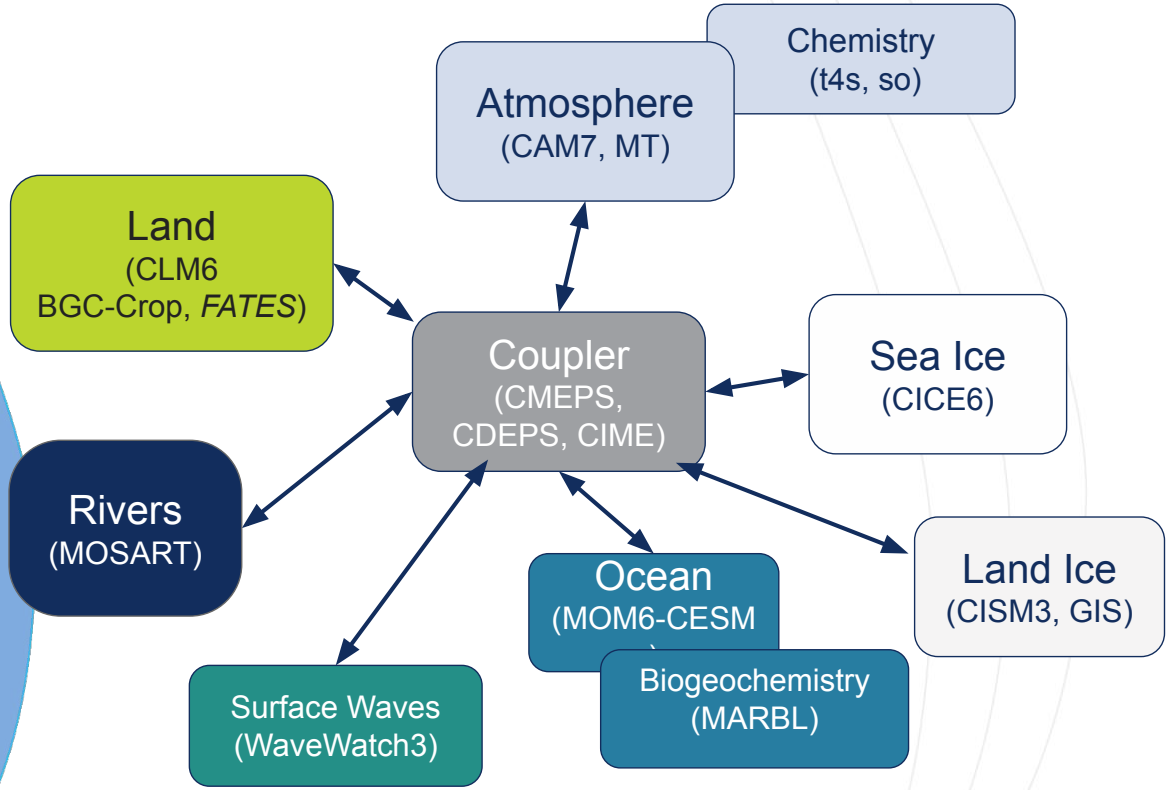


Community Earth System Model (CESM3)



Major upgrades to CESM2

- New and updated physics across component models
- Emissions-driven capabilities
- Interactive Greenland Ice Sheet
- New Ocean and Wave models
- New atmosphere dy-core plus MPAS option



Full list of changes at cesm.ucar.edu

Selected updates for CESM3

Atmosphere: SE dycore, enhanced vertical resolution and raised model top, updated CLUBB, PUMAS microphysics, RRTMGP, convective gustiness, ….

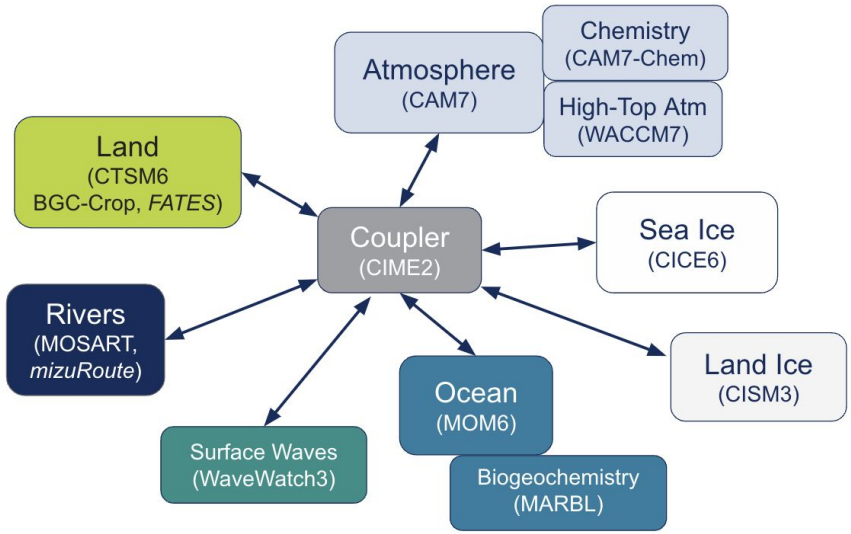
Ocean: MOM6, hybrid coordinate, variable sea level, tracer budgets within the Lab Sea, stochastic GME, isopycnal diffusion (Redi), …

Sea-ice: advanced snow physics, grounded sea ice, and floe size distribution / wave interaction, …

Land: updated high-res surface datasets, biomass heat storage, improved crops (planting calendars, tillage, bioenergy crop types), parameter estimation, hillslopes, …

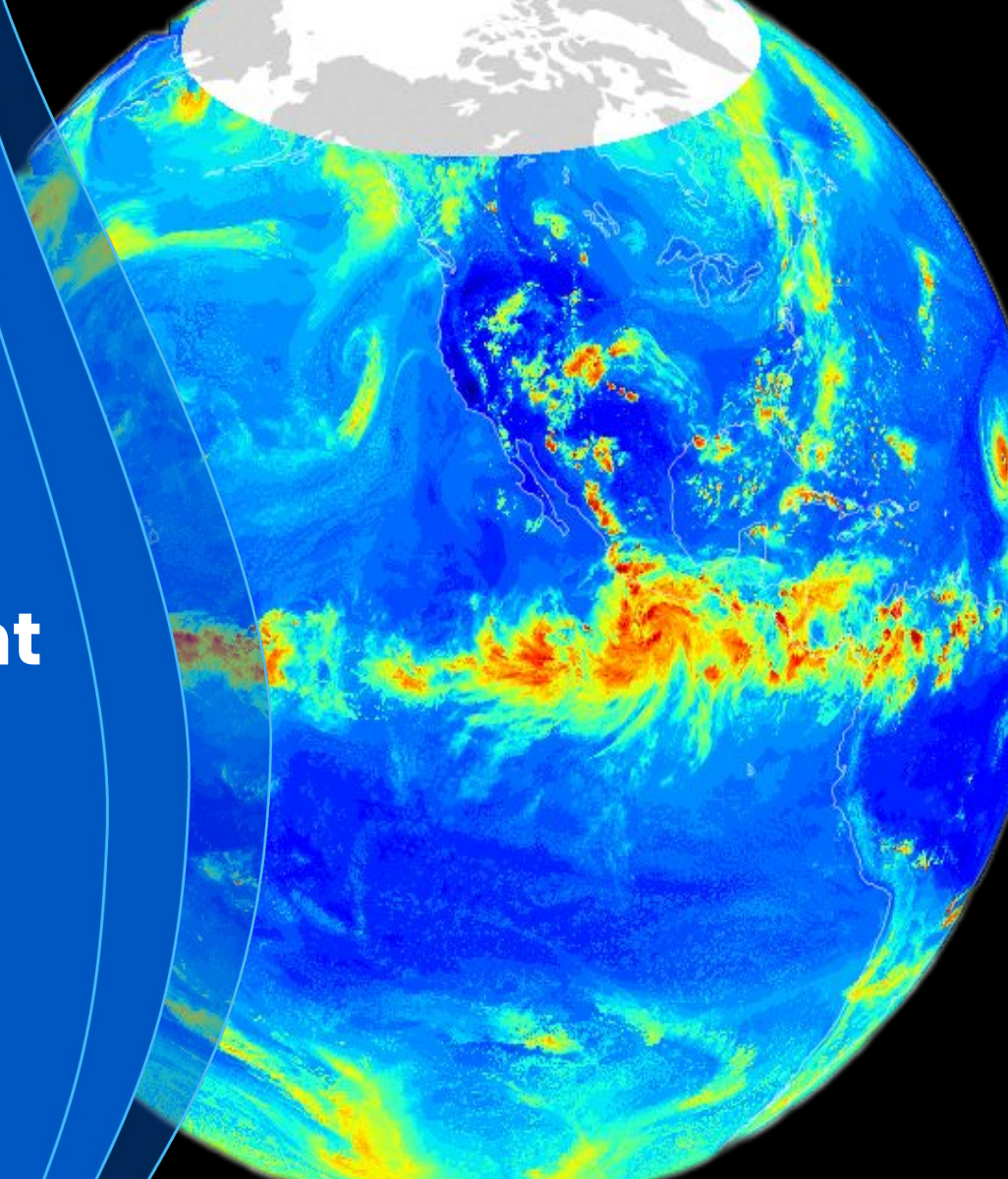
Land-ice: Dual polar ice sheet capability, ice-ocean interactions, basal sliding and calving schemes

Chemistry: Tropospheric UV radiation, new dust emissions, interactive fire aerosol emissions, …



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CESM3 Development and Spinup

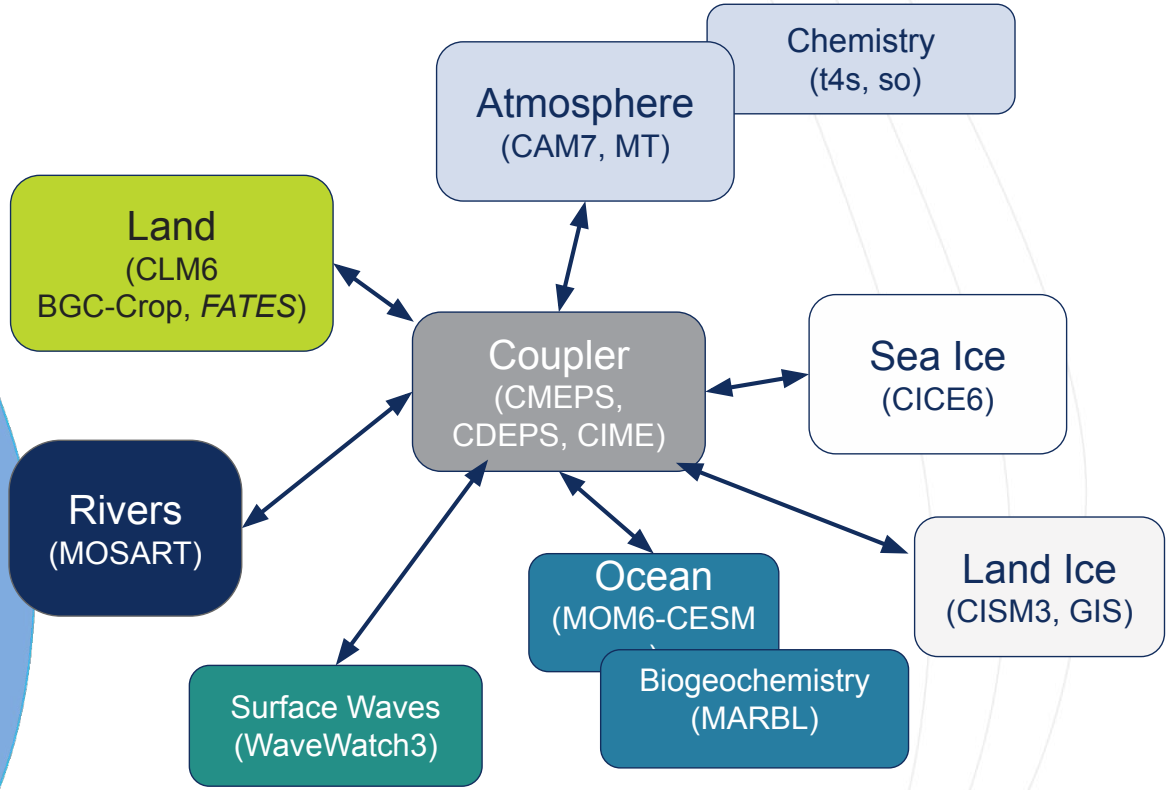


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- Emissions-driven capabilities
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- New Ocean and Wave models
- New atmosphere dy-core plus MPAS option
- Select new physics across component models



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Community Earth System Model (CESM3)



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Status update:

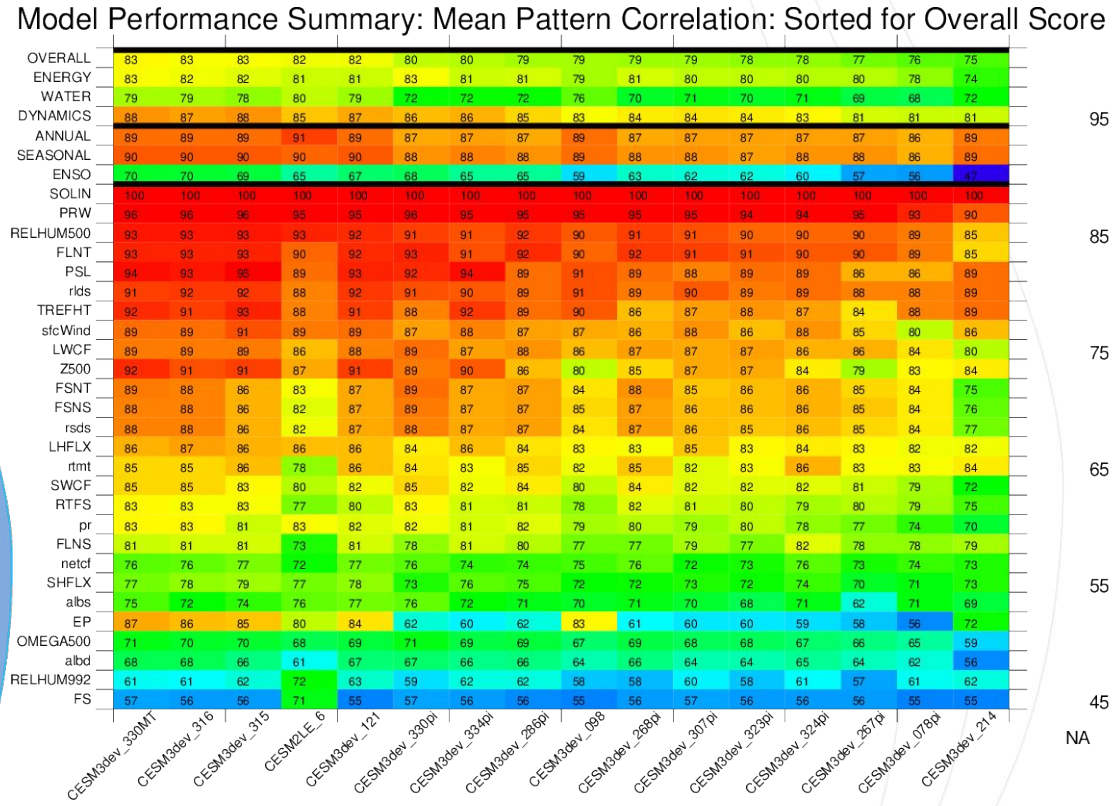
- CESM3 is 'finalized' and we are spinning up towards emissions-driven capability
- CESM3 development has been just as challenging as prior versions with
  - old and new biases
  - difficult to resolve pathological behavior
  - tuning tradeoffs
- Fortunately, preliminary indications are that the final version will represent an improvement over CESM2 in many metrics

Community Earth System Model (CESM3)



CESM2 was a very good model in terms of variability (ENSO etc…) - CESM3 is getting better

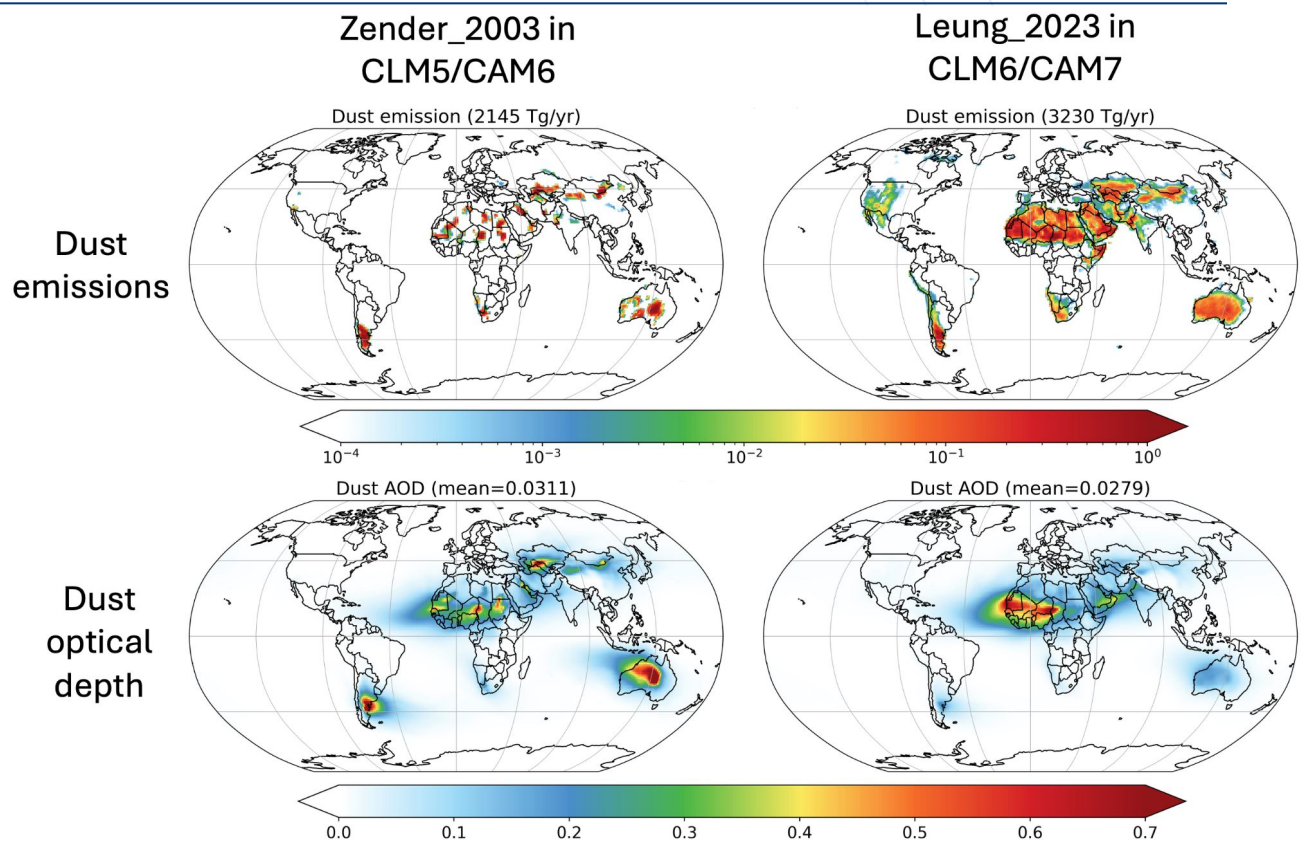
- Red is good
- Left column is best overall
- Very left is a newer variant of CESM3 (beating well-tuned CESM2)



New dust emissions representation

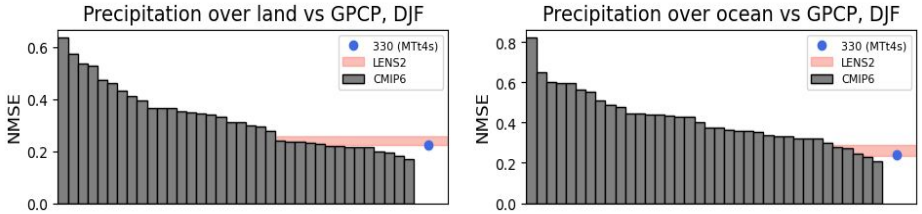
CESM3 uses Leung et al. (2023) dust emissions

- Zender 2003 dust emissions are spatially discontinuous across the globe
- Leung 2023 simulates spatially continuous dust
- Dust optical depth reasonably peaks in the Sahara

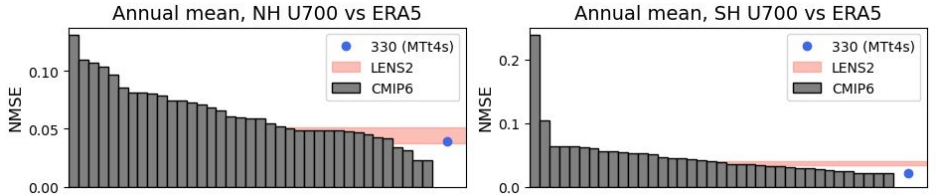


Normalized mean squared error of various climate metrics

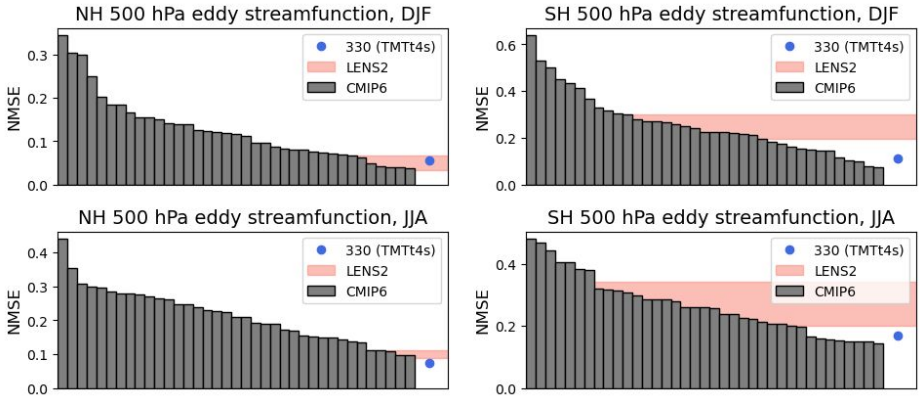
Precipitation



700 hPa zonal wind



500 hPa eddy stream function



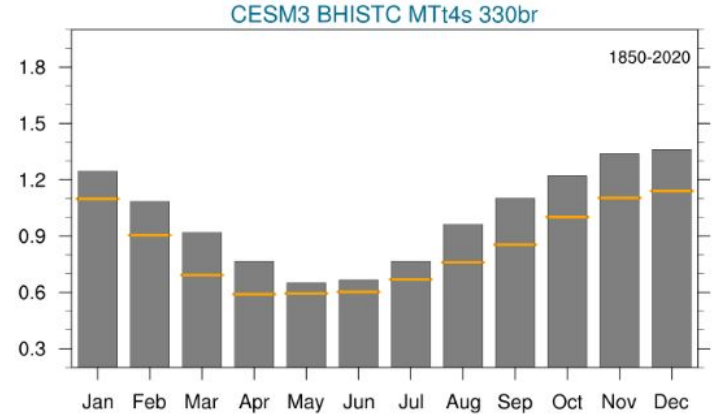
250 hPa velocity potential

- Precip: as good or slightly better than CESM2
- U700: Improvements in the Southern Hemisphere
- Stationary waves (500 hPa eddy stream function): as good or slightly better than CESM2 in the NH, substantial improvements in the SH
- Global divergent circulation (250 hPa velocity potential): slight degradation in DJF, as good as CESM2 in JJA

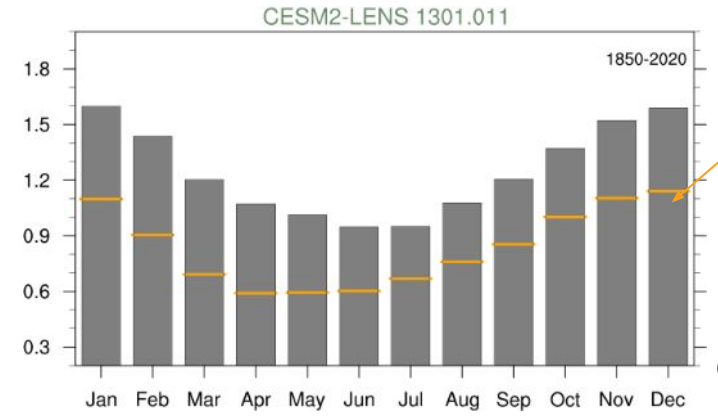
NSF NCAR OPERATED BY UCAR

ENSO in CESM3 vs CESM2

Monthly Nino3.4 standard deviation

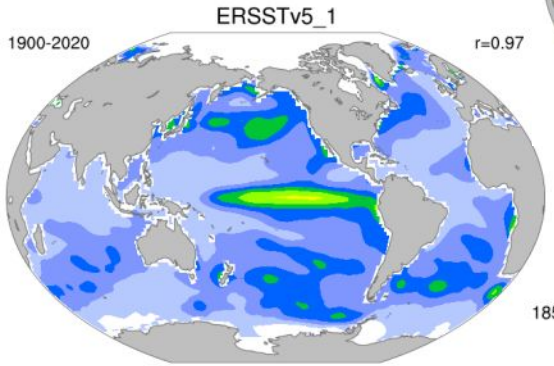


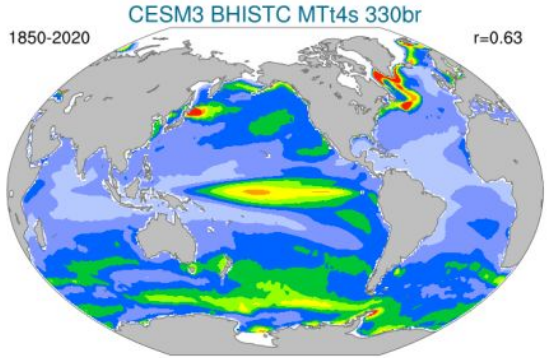
CESM3

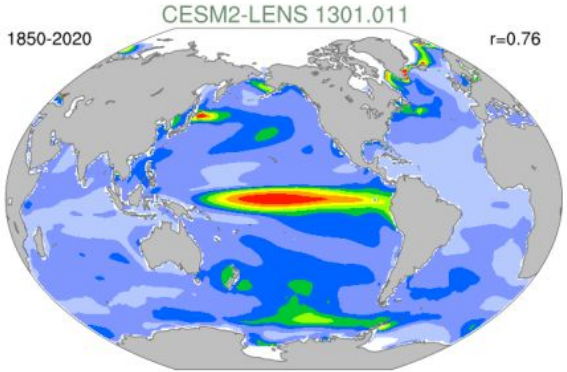


CESM2

Obs

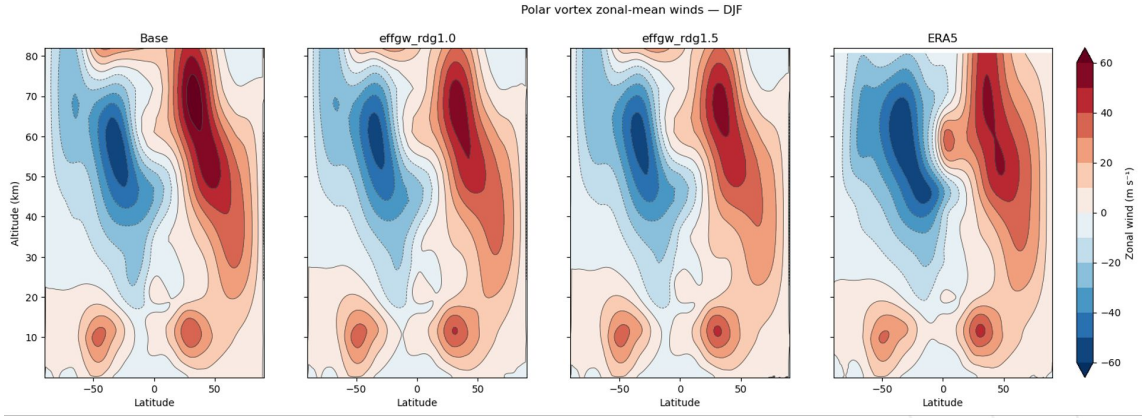


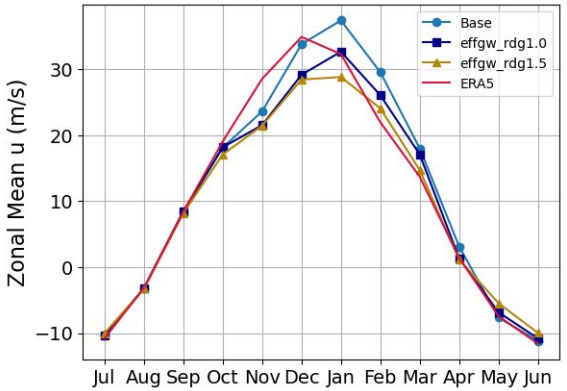


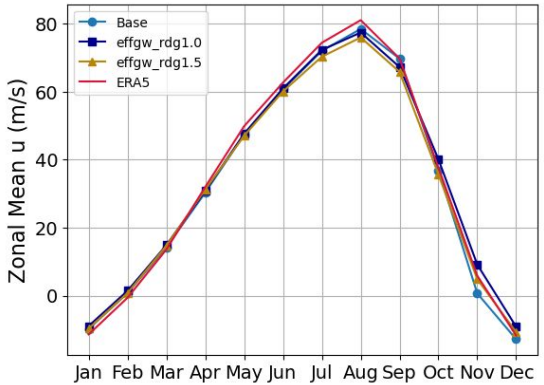


Final Tuning of Polar Vortex

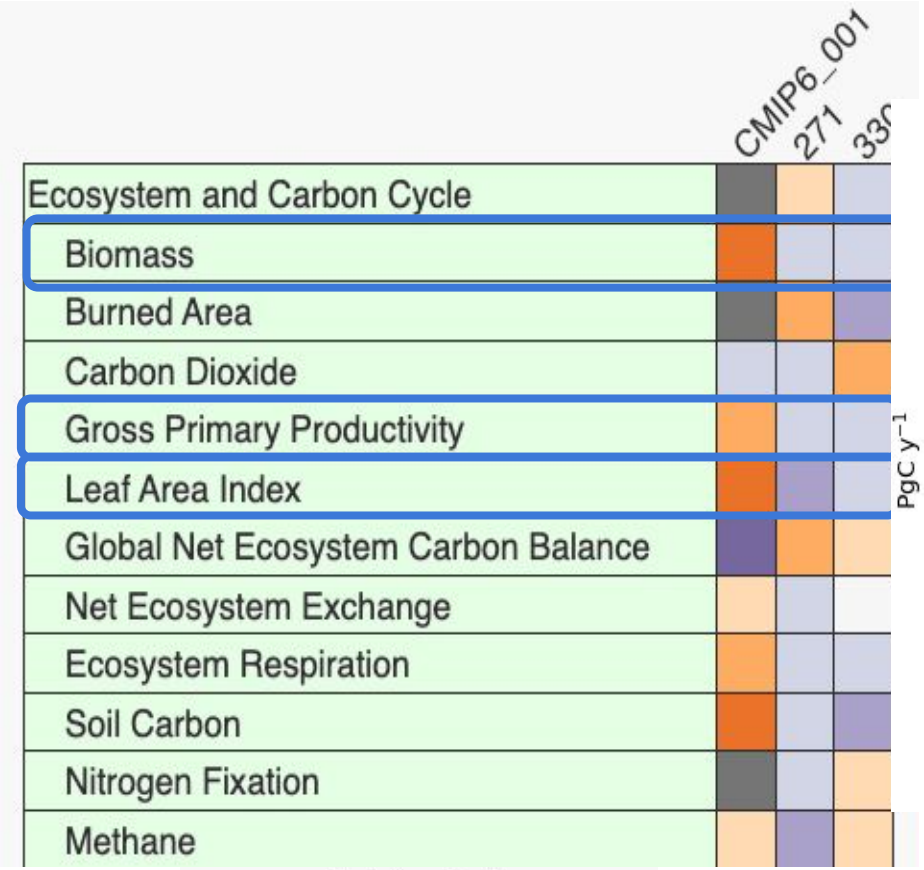
- Wind speed and tilt of jet axis has been a long-standing challenge, but much improved in CESM3
- Improvements seen in AMIP simulations hold true for fully coupled simulations (B-cases)
- Final tuning ongoing

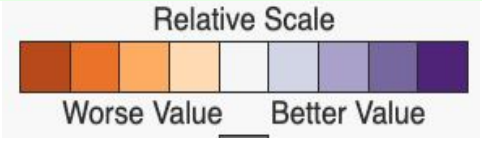


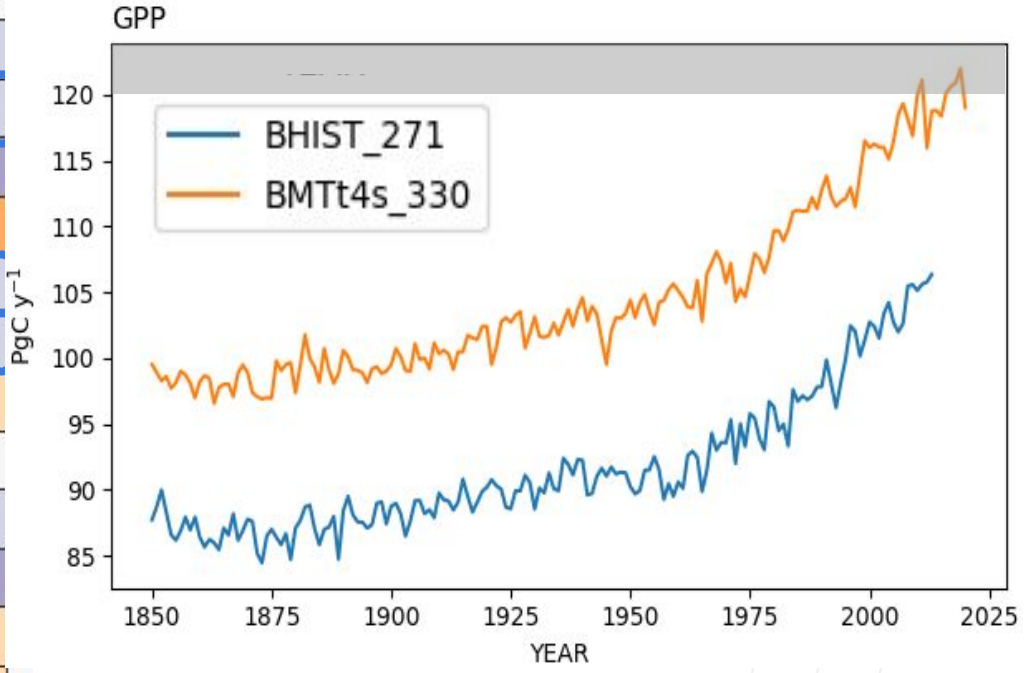




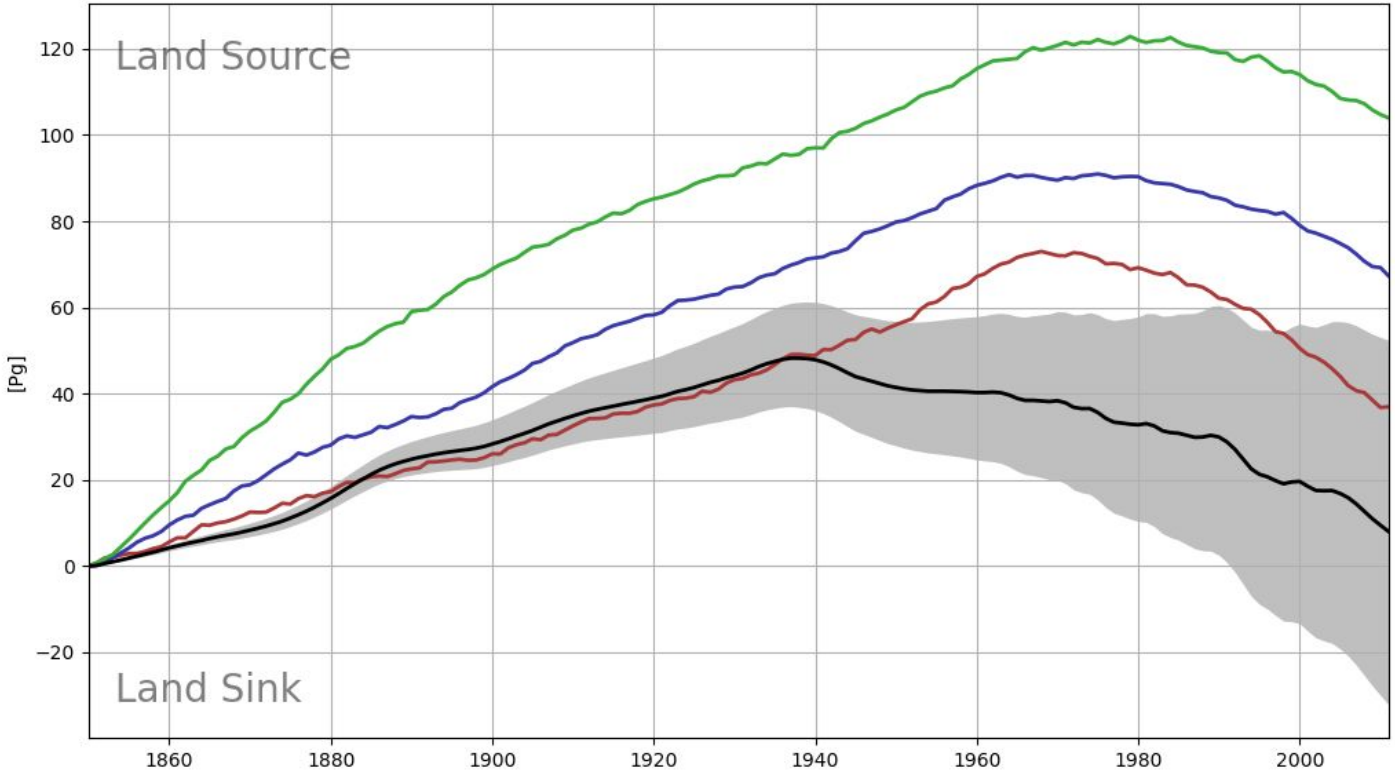
Land Tunings (B-case June 2026)







CESM3 Spinup Required



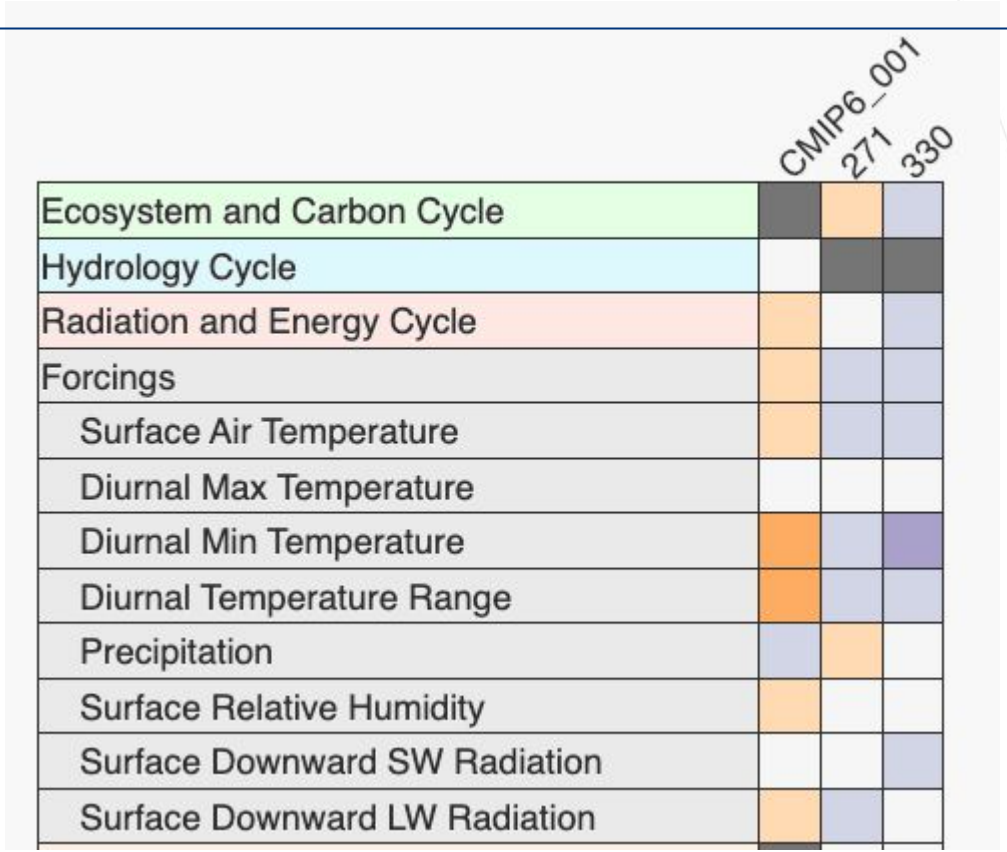
271 (Feb)

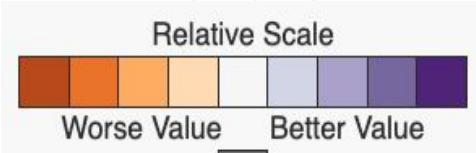
330 (June)

CESM2

“Obs”

CESM3 Climate (coupled test sim: June 2026)





Final tuning to ocean BGC

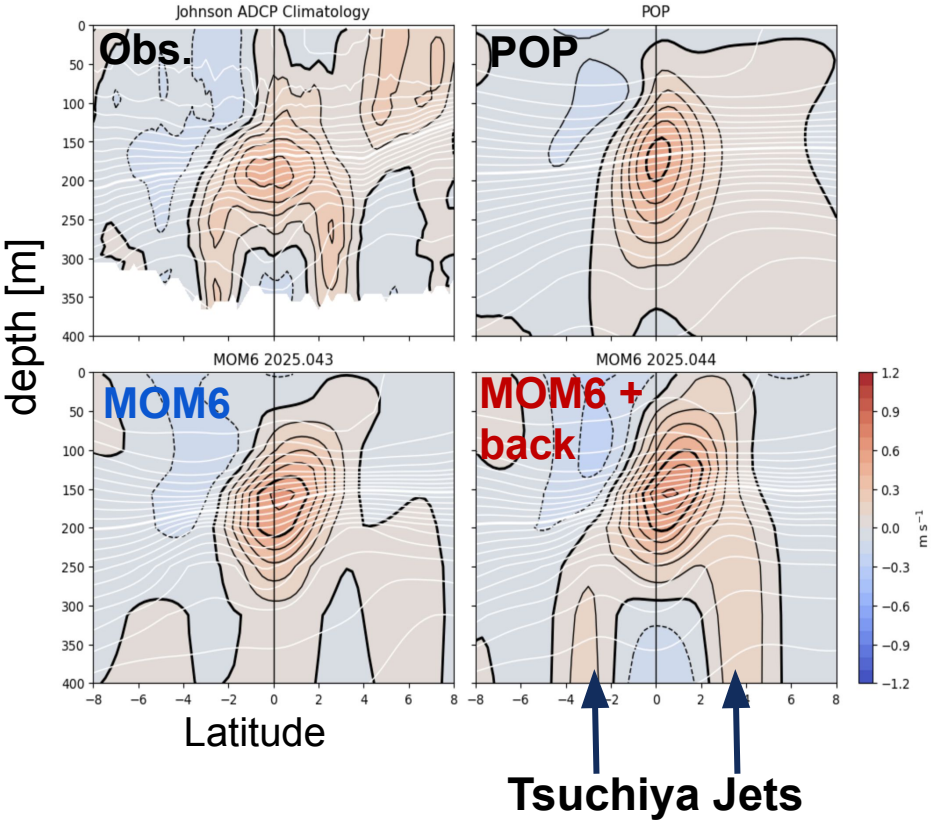
Full ocean BGC diagnostics here

Global ocean BGC metrics

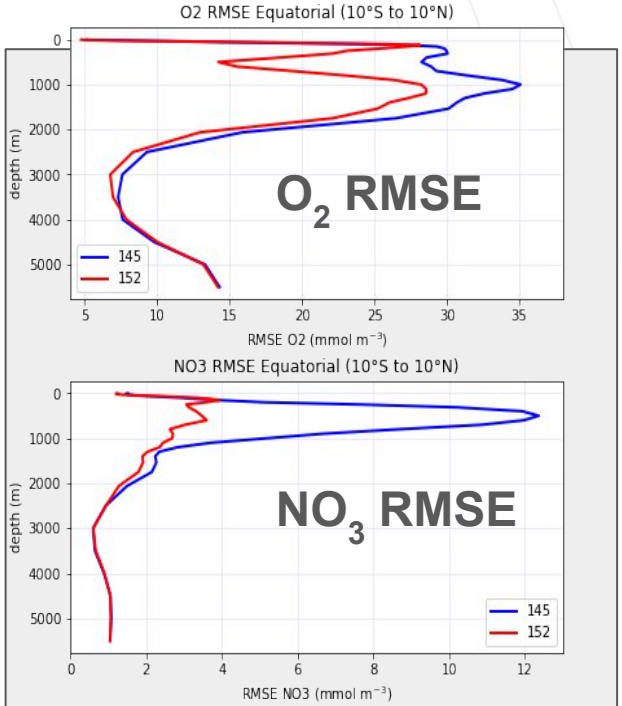
	Metric	unit	CESM	Obs	Reference
0	NPP	Pg C yr^{-1}	48.30	45 to 65	Behrenfeld & Falkowski 1997; Carr et al., 2006...
1	POC export 100m	Pg C yr^{-1}	6.47	4 to 12	DeVries & Weber, 2017
2	e-ratio	ratio	0.13	0.10 to 0.38	Doney et al., 2024
3	air-sea CO2 flux	Pg C yr^{-1}	-0.11	around 0	(for preindustrial run; negative = into ocean)
4	%NPP by diatoms	%	34.50	40%	Nelson et al., 1995
5	Silicification	Tmol Si yr^{-1}	118.86	100 to 190	Nelson et al., 1995; Holzer et al., 2014
6	Calcification	Pg C yr^{-1}	1.44	0.7 to 4.7	Liang et al., 2023; Ziveri et al., 2023 and re...
7	Nitrogen fixation	Tg N yr^{-1}	195.55	125.6 and 222.9	Wang et al., 2019
8	Microzooplankton biomass	Pg C	0.24	0.24	Buitenhuis et al., 2010
9	Mesozooplankton biomass	Pg C	0.32	0.16 to 0.19	Buitenhuis et al., 2006; Moriarty & OBrien, 2013
10	Zoo prod % of NPP	%	23.92	at least 21%	Landry and Calbet, 2004
11	Atmospheric Fe flux	Gmol Fe	33.55	around 5.5	Wiseman et al., 2023

Improved Equatorial Ocean Processes via Kinetic Energy Backscatter

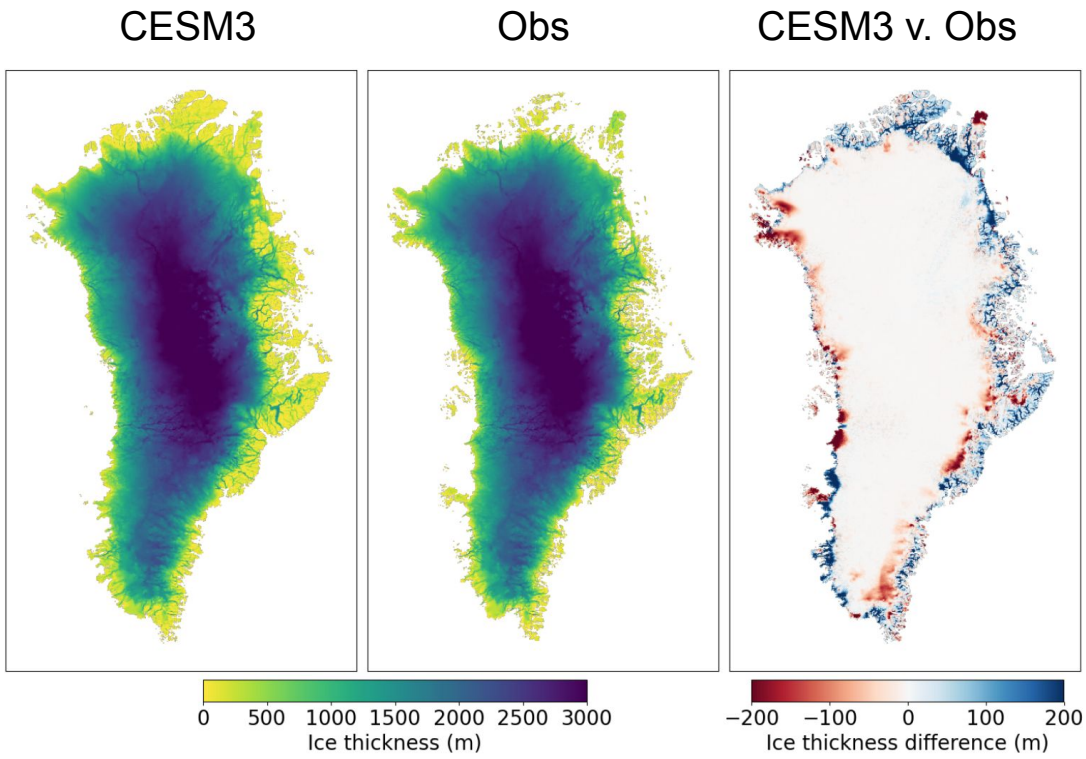
Transects of zonal velocity
165° E



- Emergence of **Tsuchiya jets** when backscatter is applied
- Jets reduce biases in extent of O2 minimum zones, critical for ocean BGC



Greenland Ice Sheet in CESM3

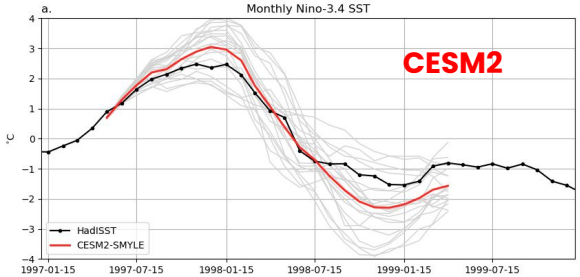


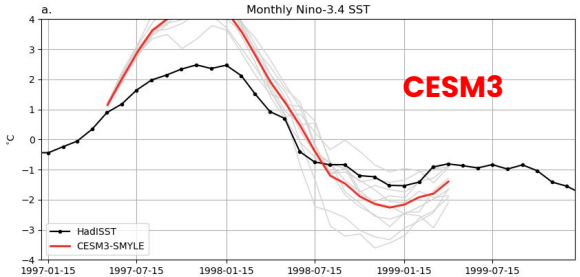
% error CESM v. Obs	CESM2	CESM3
Ice extent	15.0	7.1
Ice volume	12.2	0.003

- Initial Greenland ice sheet (spun up with preindustrial surface mass balance) is greatly improved in CESM3 compared to CESM2
- In a fully coupled spin-up CESM3-Greenland simulation, the ice sheet mass drift is ~5 Gt/yr

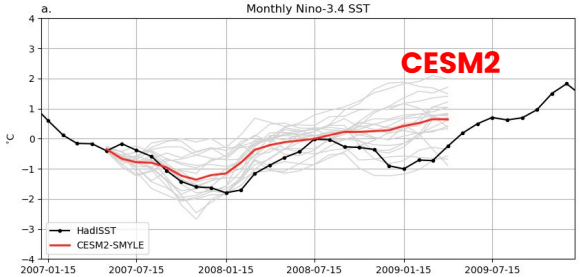
Initialized Prediction with CESM3

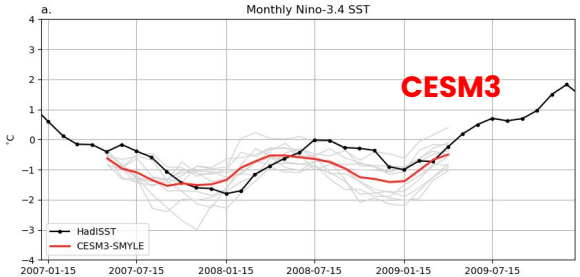
05/01/1997 Initialization:





05/01/2007 Initialization:





Work is ongoing to assess the performance of CESM3 in "SMYLE" configuration.

Preliminary comparison of 10-member CESM3 to 20-member CESM2 reveals mixed results for Niño3.4.

Forces driving the future of Earth System modeling

- **Urgent need for actionable climate change information (climate risks, consequences of intervention/mitigation, potential tipping points)**

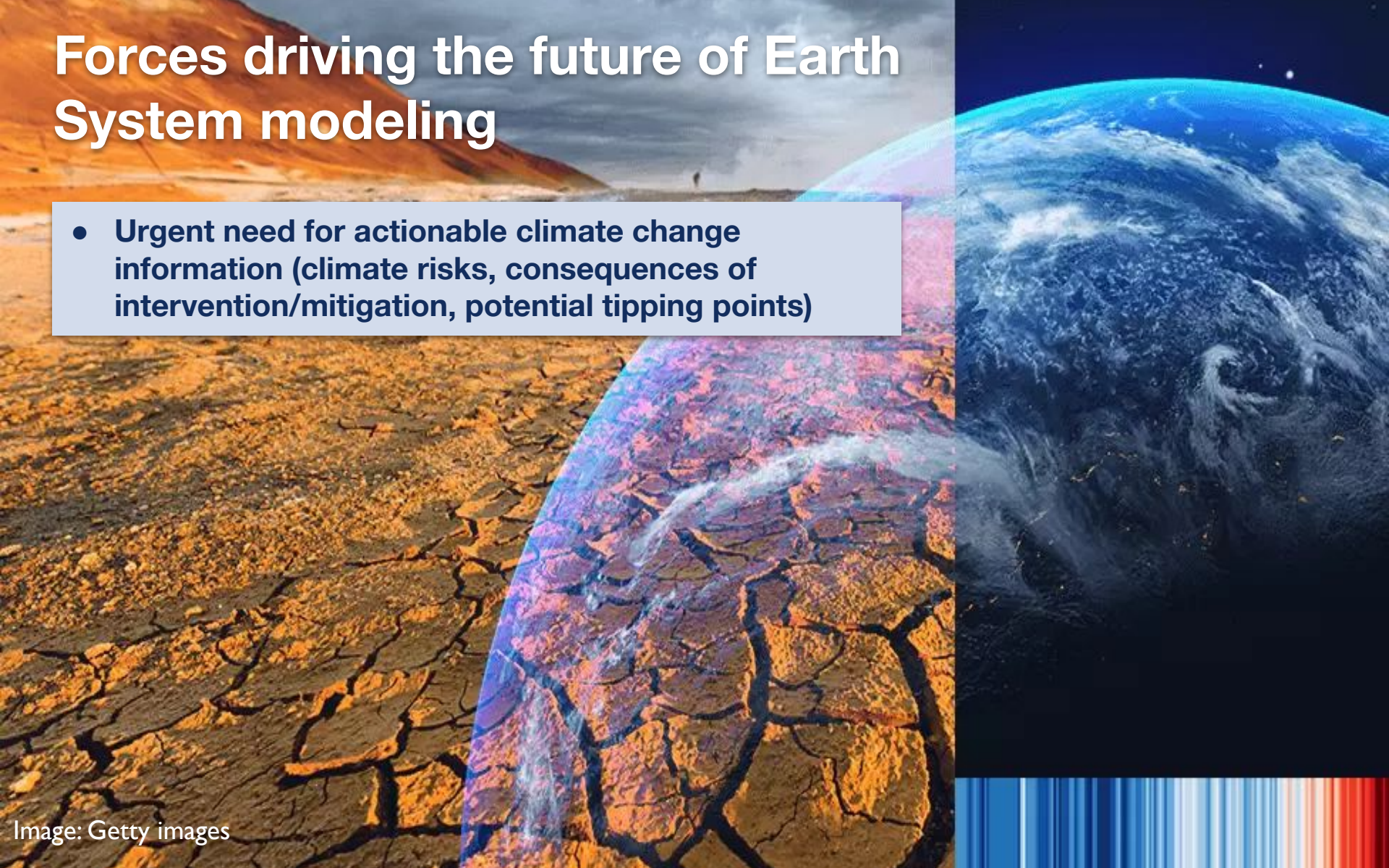


Image: Getty images



Where and when will people and ecosystems experience more extreme events?





Image: Kimon Maritz

Will we have enough water?

Or too much water?



Will we be able to grow or harvest enough food?

And can we produce it sustainably?

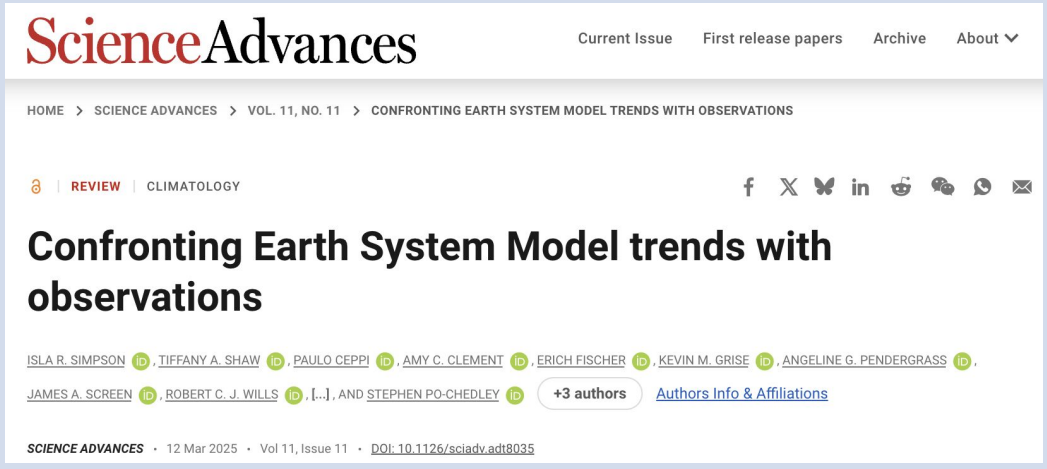




Forces that are driving the future of Earth System modeling

Evolving needs

- Actionable information
  - climate change risks and impacts for humans and ecosystems



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REVIEW | CLIMATOLOGY

Confronting Earth System Model trends with observations

ISLA R. SIMPSON, TIFFANY A. SHAW, PAULO CEPPI, AMY C. CLEMENT, ERICH FISCHER, KEVIN M. GRISE, ANGELINE G. PENDERGRASS, JAMES A. SCREEN, ROBERT C. J. WILLS, [...], AND STEPHEN PO-CHEDLEY +3 authors Authors Info & Affiliations

SCIENCE ADVANCES • 12 Mar 2025 • Vol 11, Issue 11 • DOI: 10.1126/sciadv.adt8035

Image: Getty images

Forces that are driving the future of Earth System modeling

Evolving needs

- **Actionable information**
  - **climate change risks and impacts for humans and ecosystems**
  - **potential and consequences of climate intervention (e.g., solar radiation management, carbon dioxide removal)**

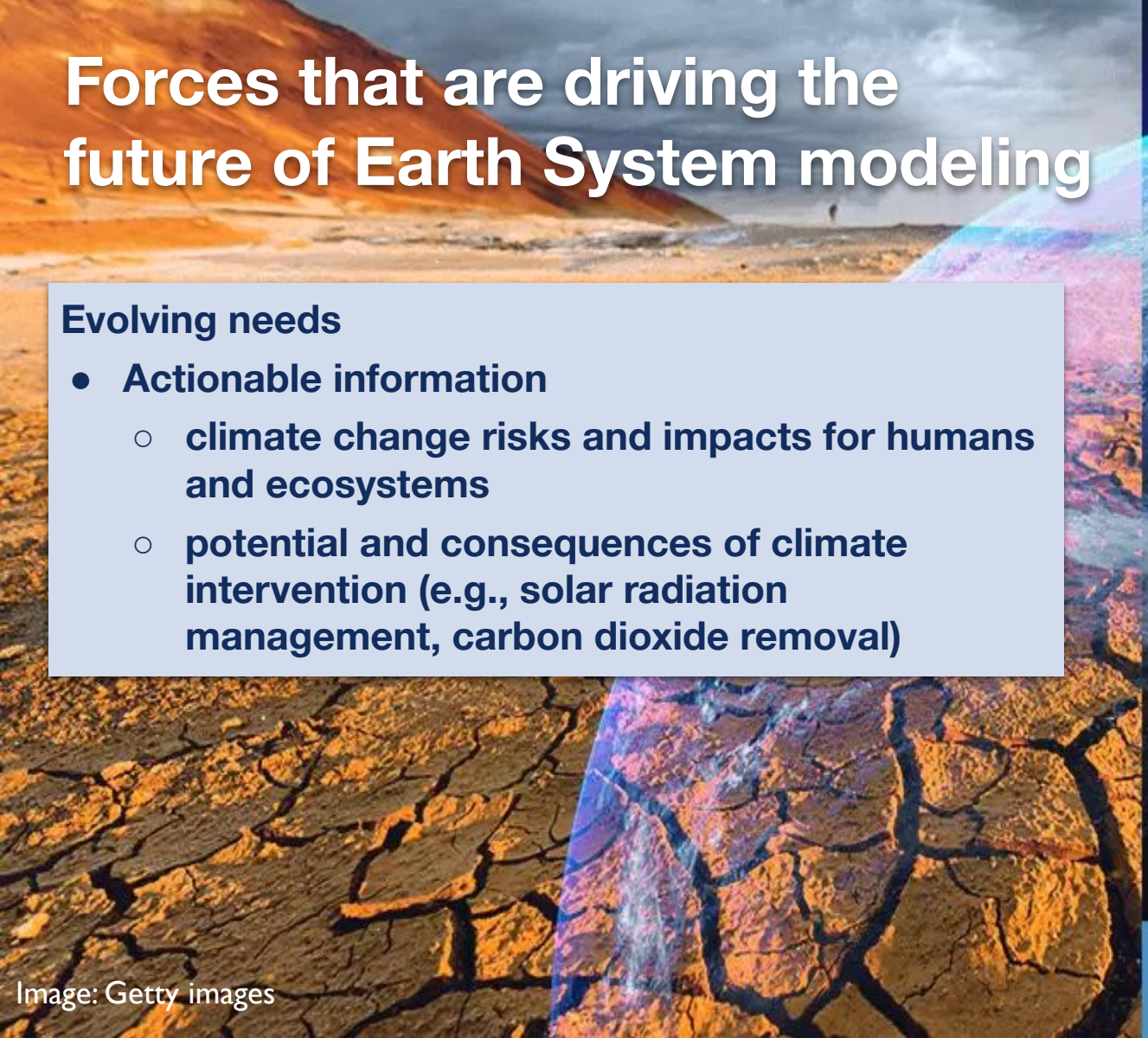






Image: Getty images



Where are we going to put the carbon (and will it stay there)?







Forces that are driving the future of Earth System modeling

Evolving needs

- **Actionable information**
  - **climate change risks for humans and ecosystems**
  - **potential and consequences of climate intervention (e.g., solar radiation management, carbon dioxide removal)**
  - **understanding potential/probability for tipping points**



Image: Getty images

Forces that are driving the future of Earth System modeling

- **Actionable information (climate risks, consequences of intervention/mitigation, tipping points)**
- **High-resolution (0.25º) and ultra high-resolution (km-scale) model configurations**
- **AI/ML: hybrid modeling, emulators**
- **Seamless Earth System Predictability research across timescales, S2S → S2D → 30-yr projections**
- **Changing computing architectures and languages and agentic AI → code modernization**
- **Calls for improved accessibility of ESMs and output (e.g., to global south)**

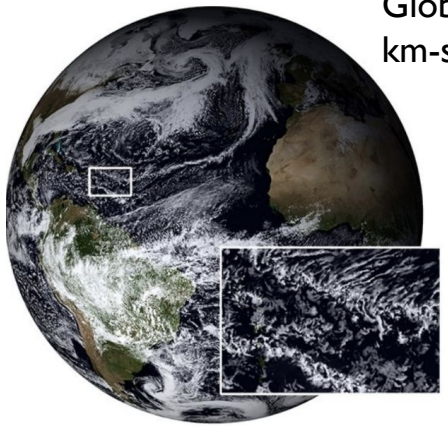
Image: Getty images

These drivers present opportunities and challenges for the CESM activity

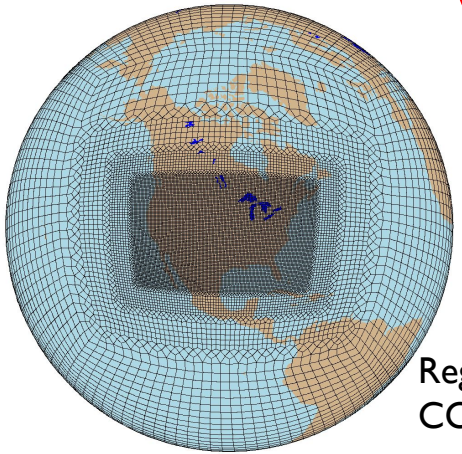


CESM high-resolution progress and plans

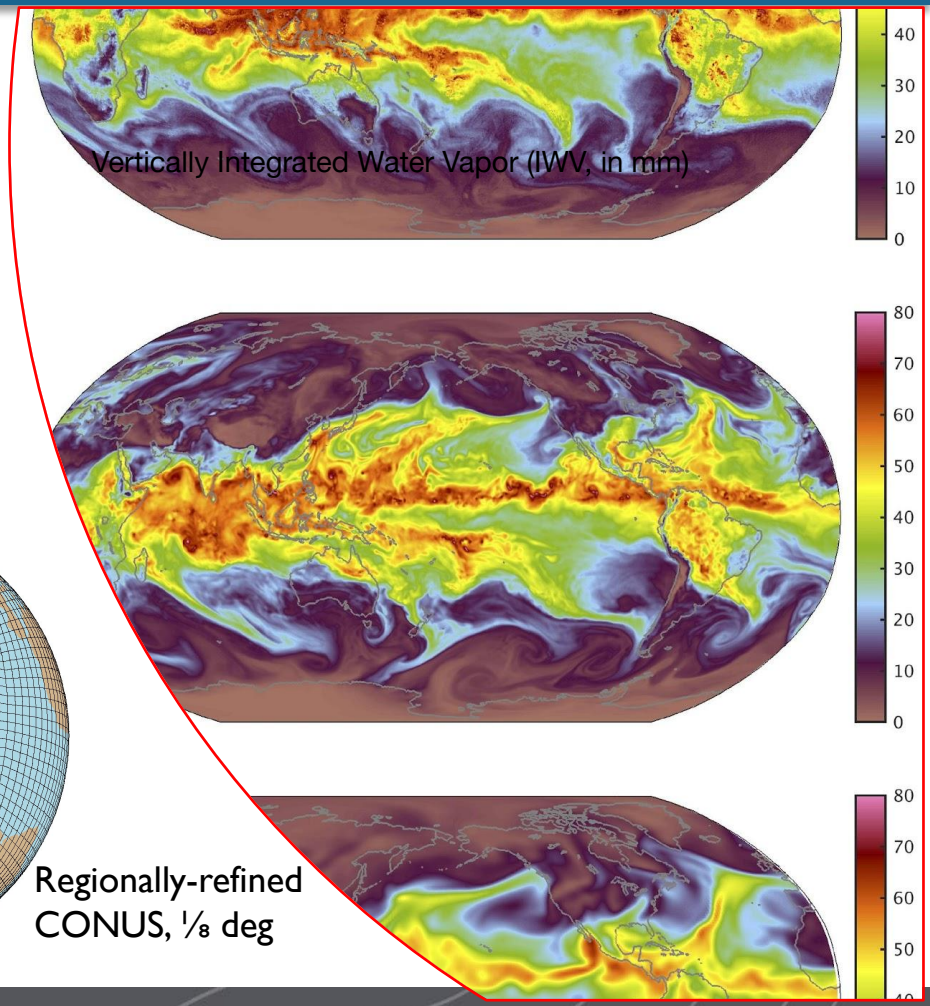
- CESM1.3(HR): 0.25° atm/lnd, 0.1° ocn
- Developing CESM3 HR version
- CESM EarthWorks and STORMspeed projects developing km-scale configurations with MPAS and NH-SE dynamical cores
- Several regionally-refined grids available, including South America (6km i



Global
km-scale



Regionally-refined
CONUS, ⅛ deg



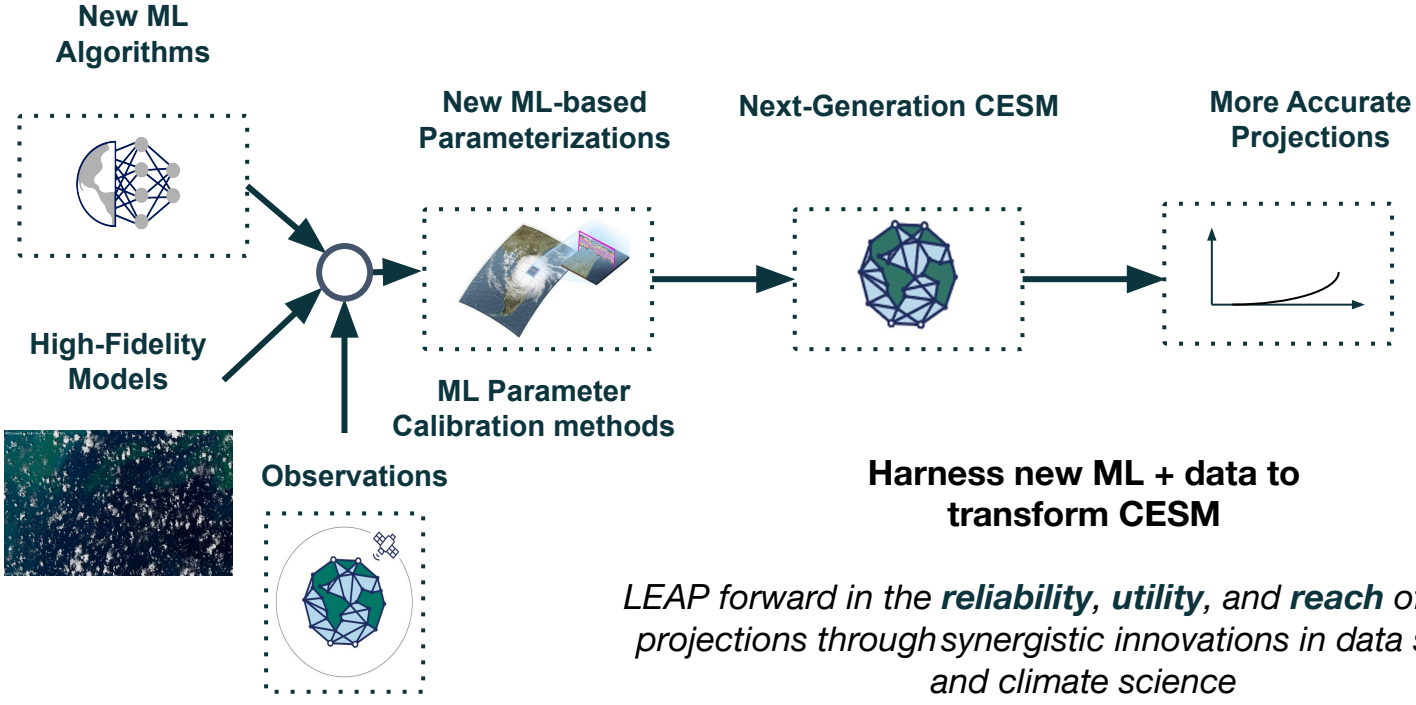
Chang et al. (2020, JAMES)

Towards a hybrid (physics + Machine Learning) version of CESM (CESM3-MLe)

LEAP

Learning the Earth with Artificial intelligence and Physics
NSF Science and Technology Center

M²LInES
Schmidt Futures



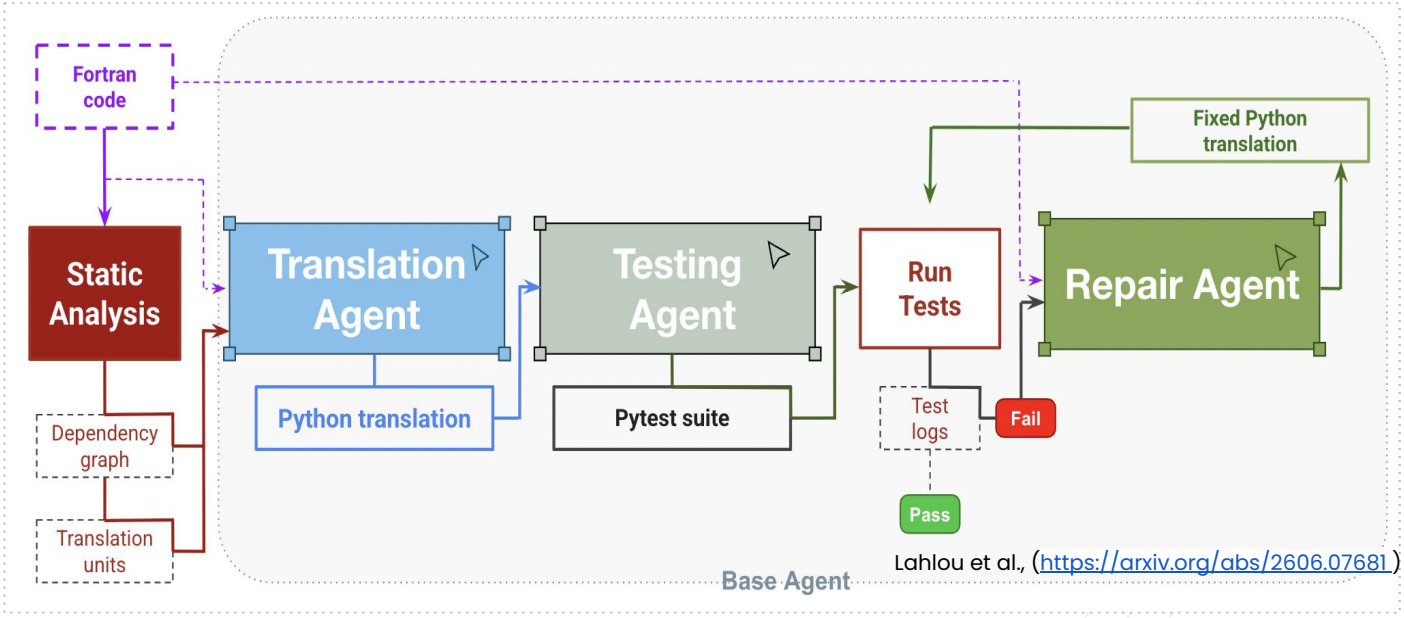
Harness new ML + data to transform CESM

*LEAP forward in the **reliability**, **utility**, and **reach** of climate projections through synergistic innovations in data science and climate science*

AI-assisted code translation

Motivation: Accessible, modernized, architecture-agnostic, differentiable code base

- CLM multi-layer canopy converted to JAX
- Prototype partial conversion of CESM2 to PyTorch (LENS configuration)
- MOM6 conversion to GPU-ready framework
- …
- Code shadows?

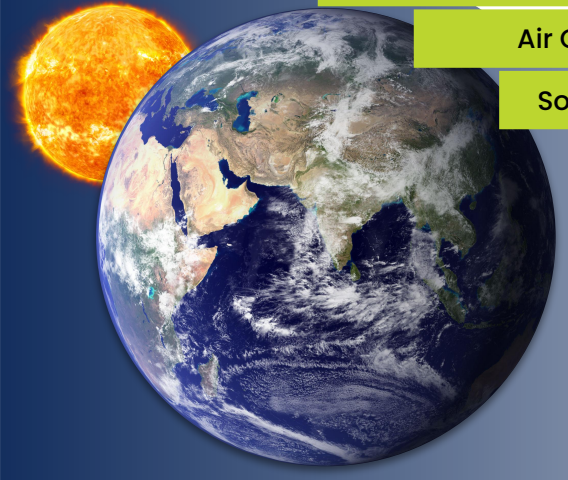


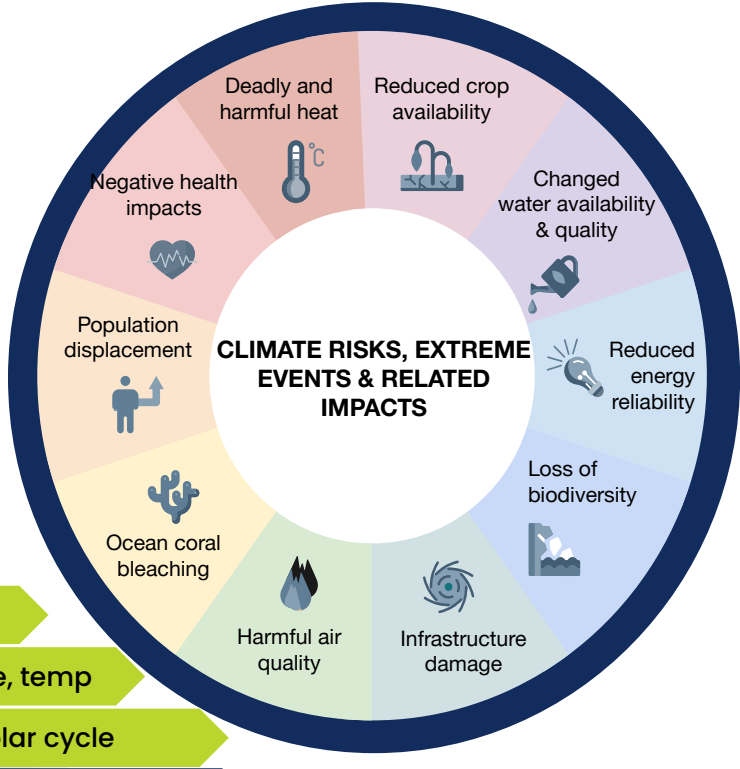
Lahlou et al., (https://arxiv.org/abs/2606.07681)

NSF NCAR priority: Earth System Predictability Across Timescales (ESPAT)

Guided by societal needs, spanning minutes to centuries

- Tornadoes
- Flooding
- Solar Flares/CME
- Storm Surge
- Wildfires
- Air Quality
- Solar Rossby Waves
- Heat/Cold Waves
- Drought/floods
- Seasonal Temp & Precip
- Sea-ice, land-ice
- Sea-level rise, temp
- Solar cycle



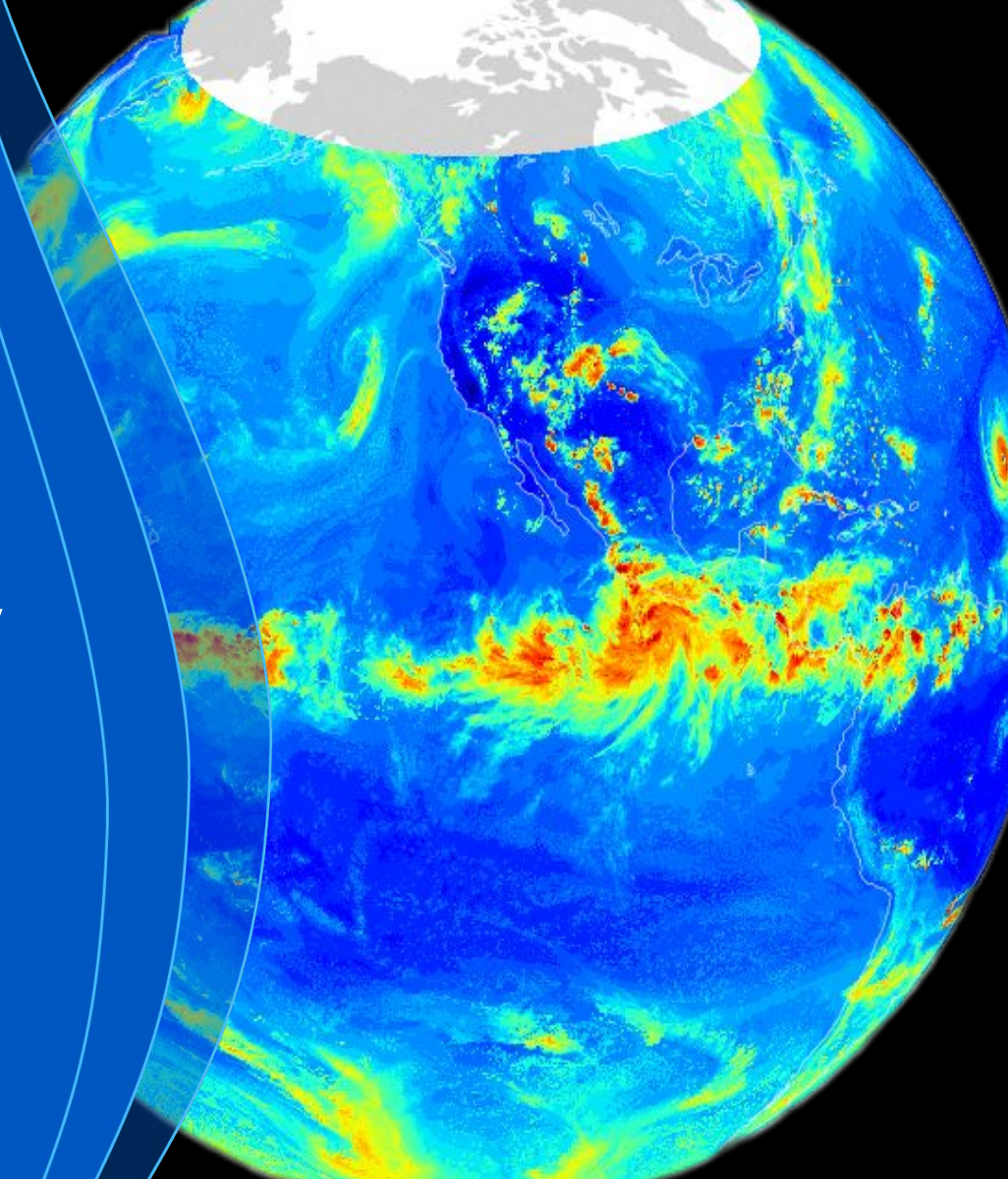


Minutes → Centuries

NSF NCAR working with research community to define near- and long-term priorities

NCAR
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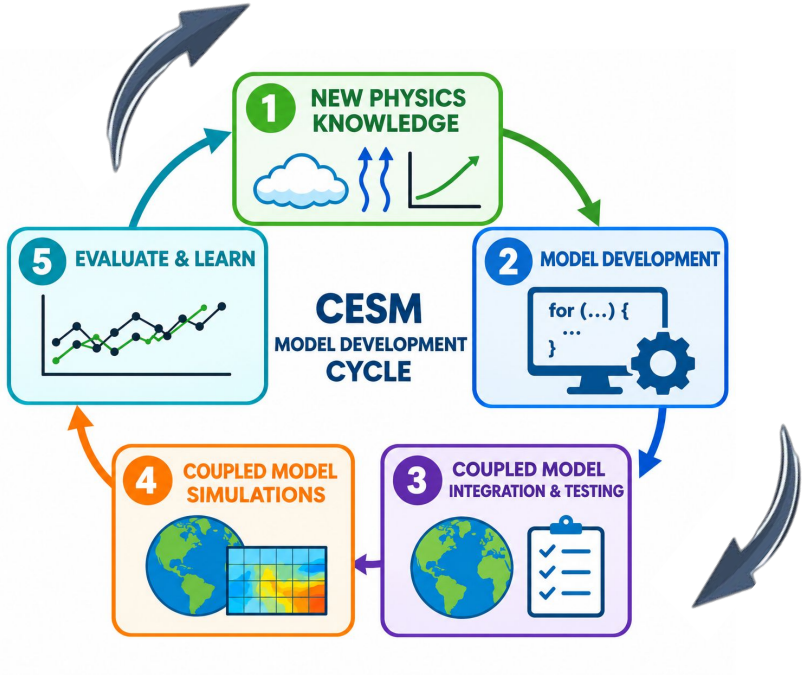
A vision for a faster, more agile, and more skillful CESM

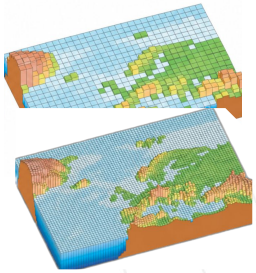


A vision for a faster, more agile, and more skillful CESM

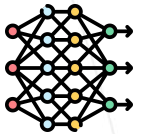


Need for more reliable climate and weather information at a range of time and space scales to understand risks, to prepare for disasters, and to learn how we can respond to a changing planet





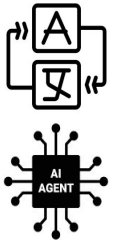
Enhanced multi-scale capability



AI/ML for accuracy and speed

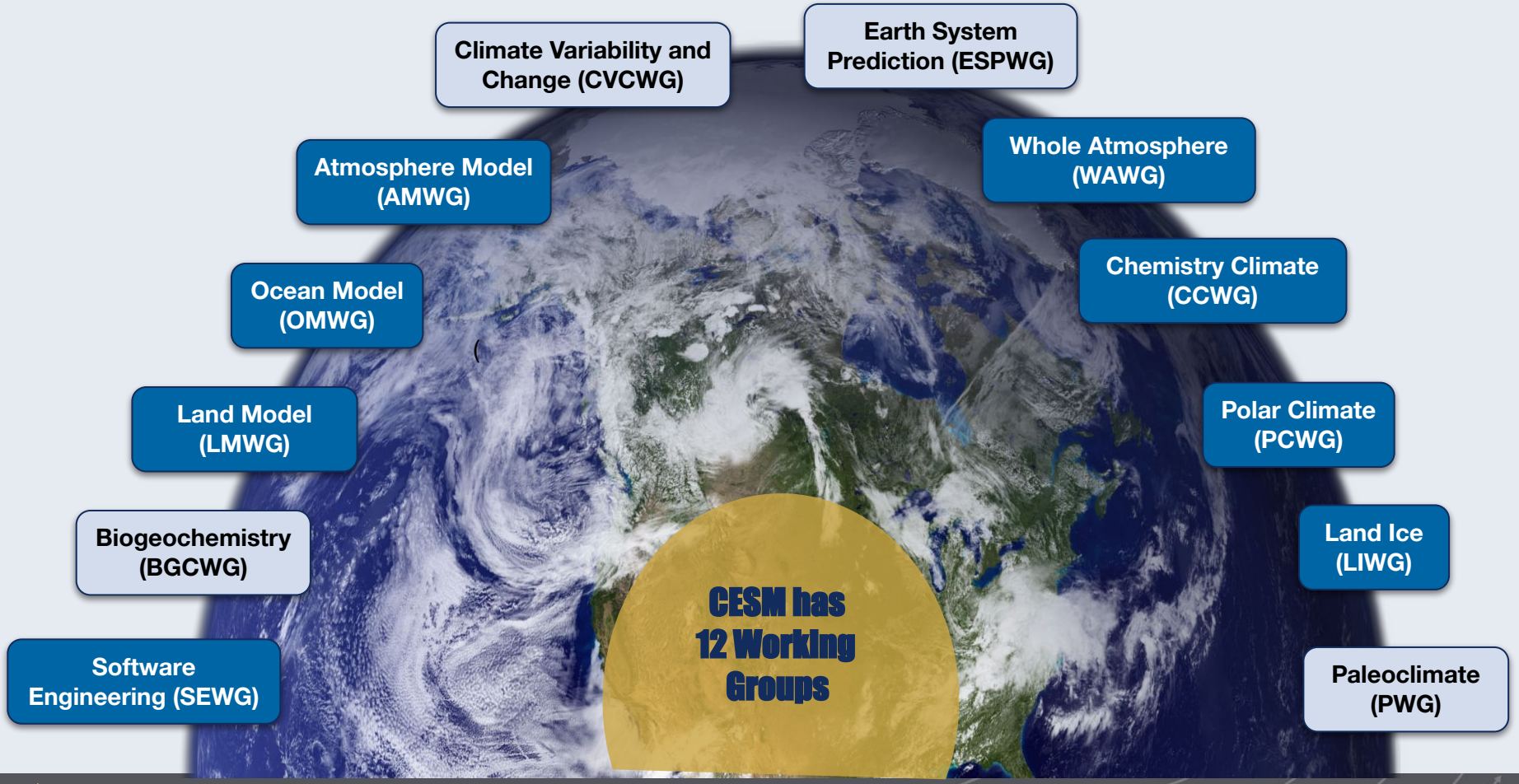


Streamlined use of Earth observations

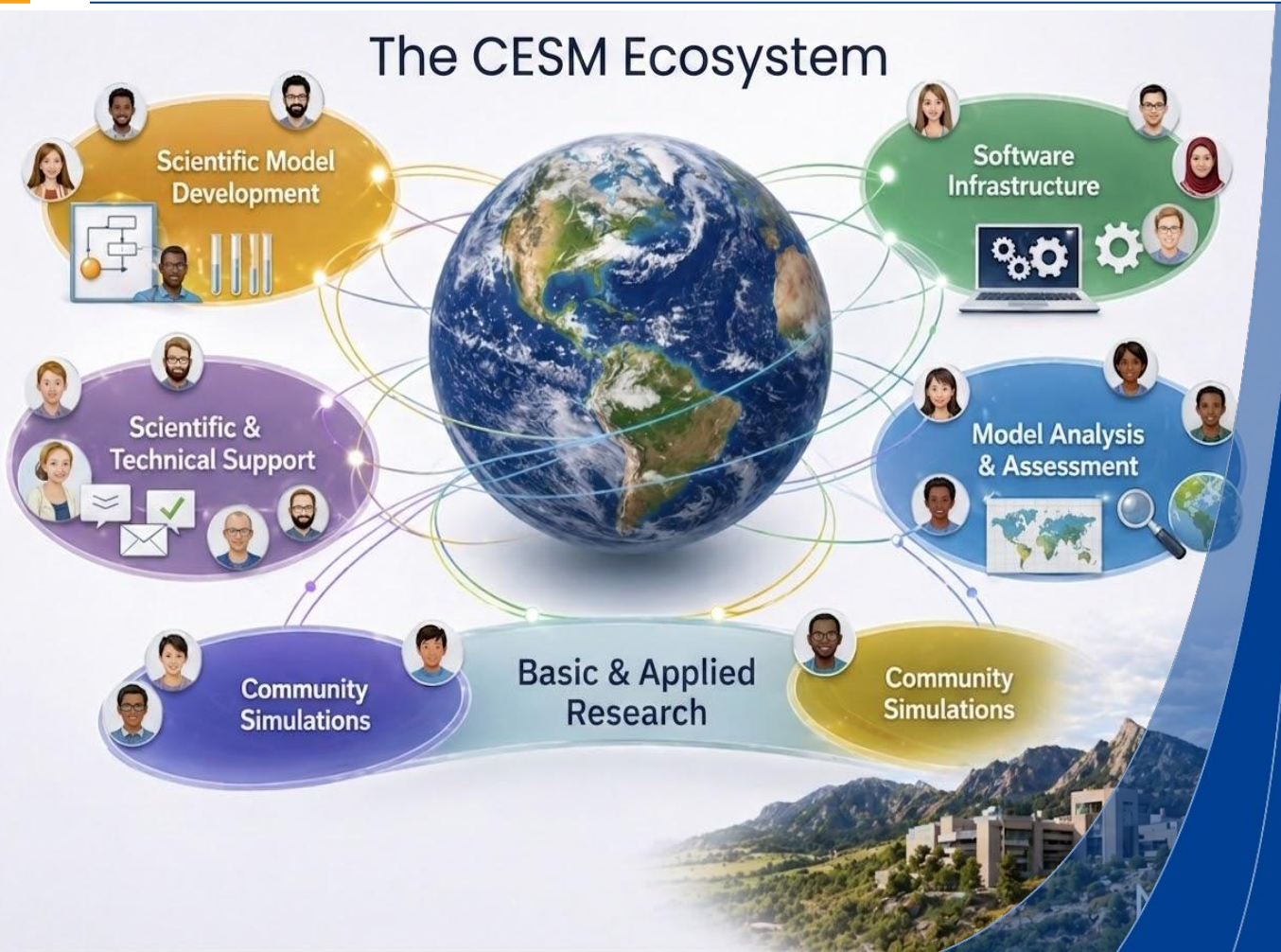


AI-assisted code modernization

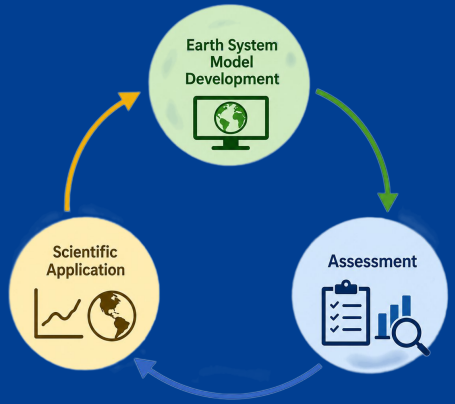
CESM Working Groups provide platform for engaged community model development and application



NSF NCAR provides the backbone of the CESM Ecosystem, but the Community makes it thrive



CESM thrives through intertwined team of NCAR and Community scientific and technical staff that deliver improved innovative and impactful science, simulation quality, new model capabilities, and community simulation datasets



Learning and engagement opportunities



Tutorials

- CESM Tutorial (80+ students, online materials)
- Jupyter notebooks

Mentoring

- NCAR CESM staff host graduate students / postdocs / and faculty visits

Workshops

- CESM Annual Workshop (June)
- Winter Working Group meetings (February)

32nd Annual CESM Workshop (June 14-16, 2027)



In person and virtual options

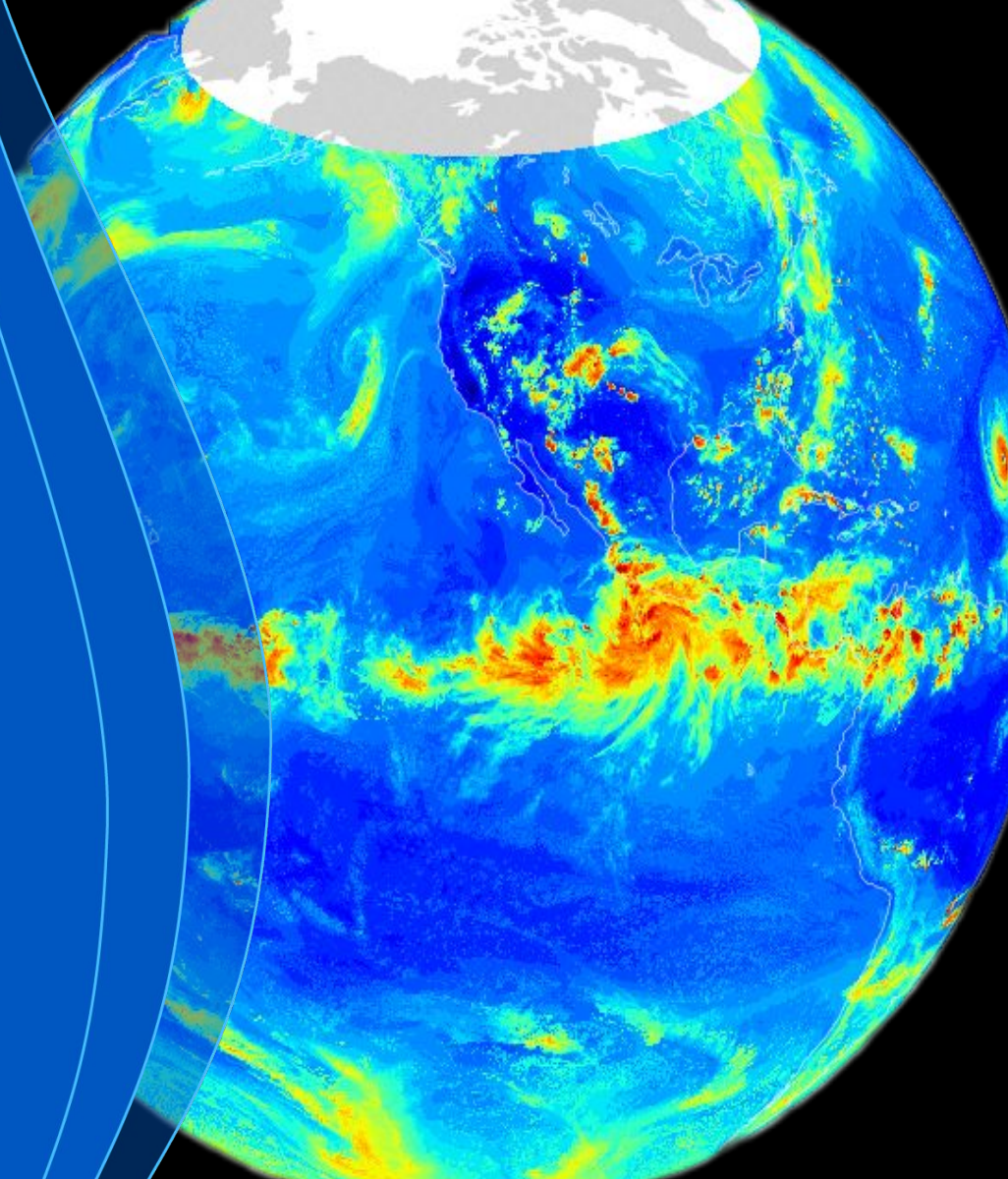
31st Annual Workshop

210+ presentations from 150 unique institutions



NCAR
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Thanks and Welcome to the CESM Community



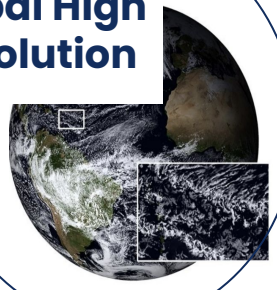
Unified modeling framework

“Pick and Choose” menu of options

–

All components interact and are ready to play

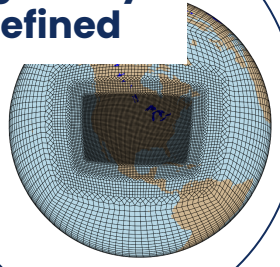
Global High Resolution



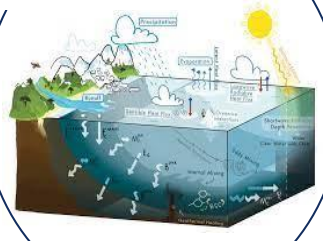
Global Low Resolution



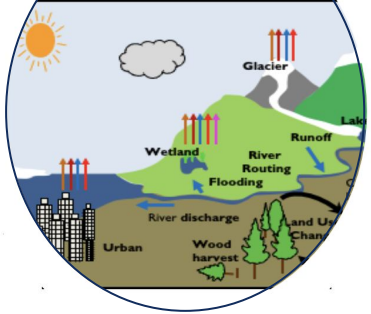
Regionally-refined



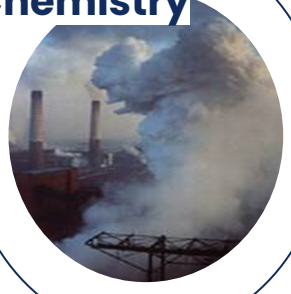
Ocean



Land / Hydrology



Chemistry



Space Weather

