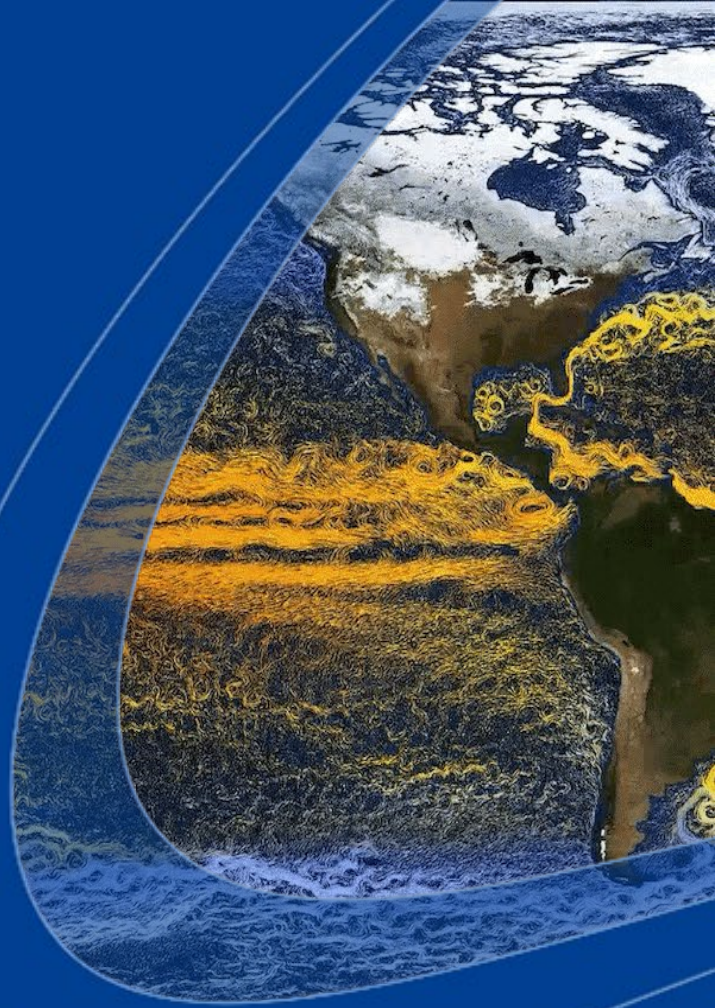
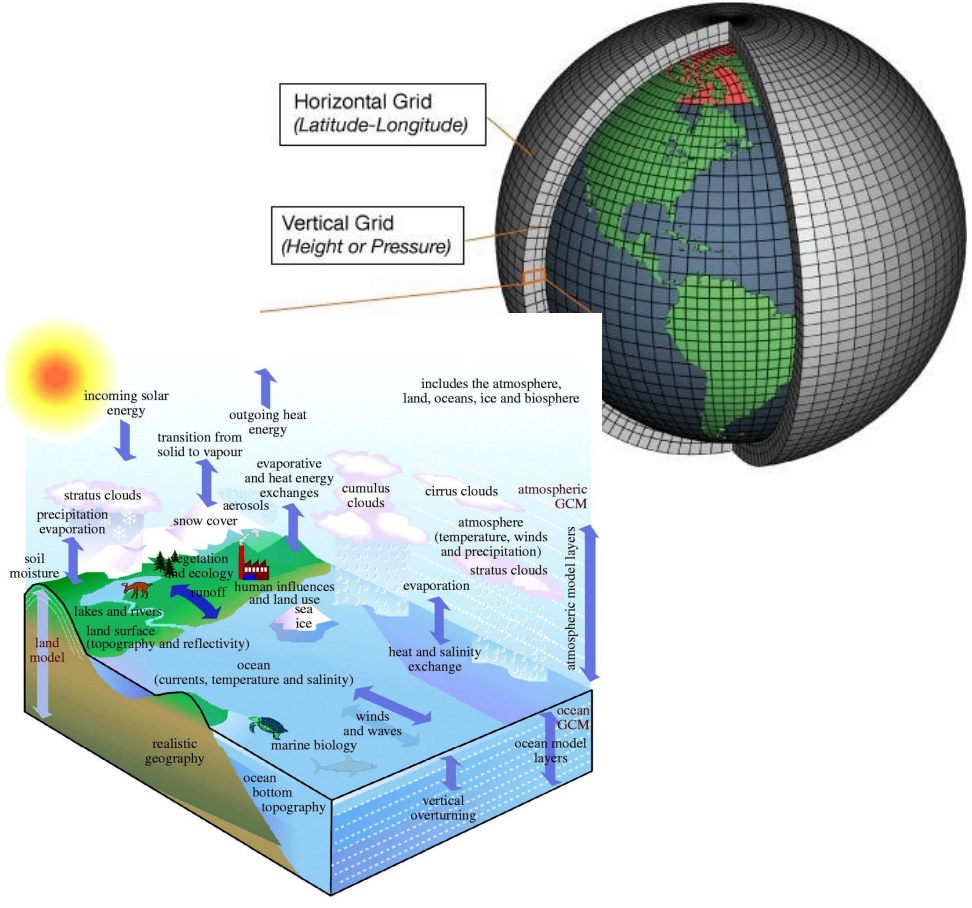
Introduction to the Community Earth System Model (CESM)

David Lawrence
CESM Chief Scientist

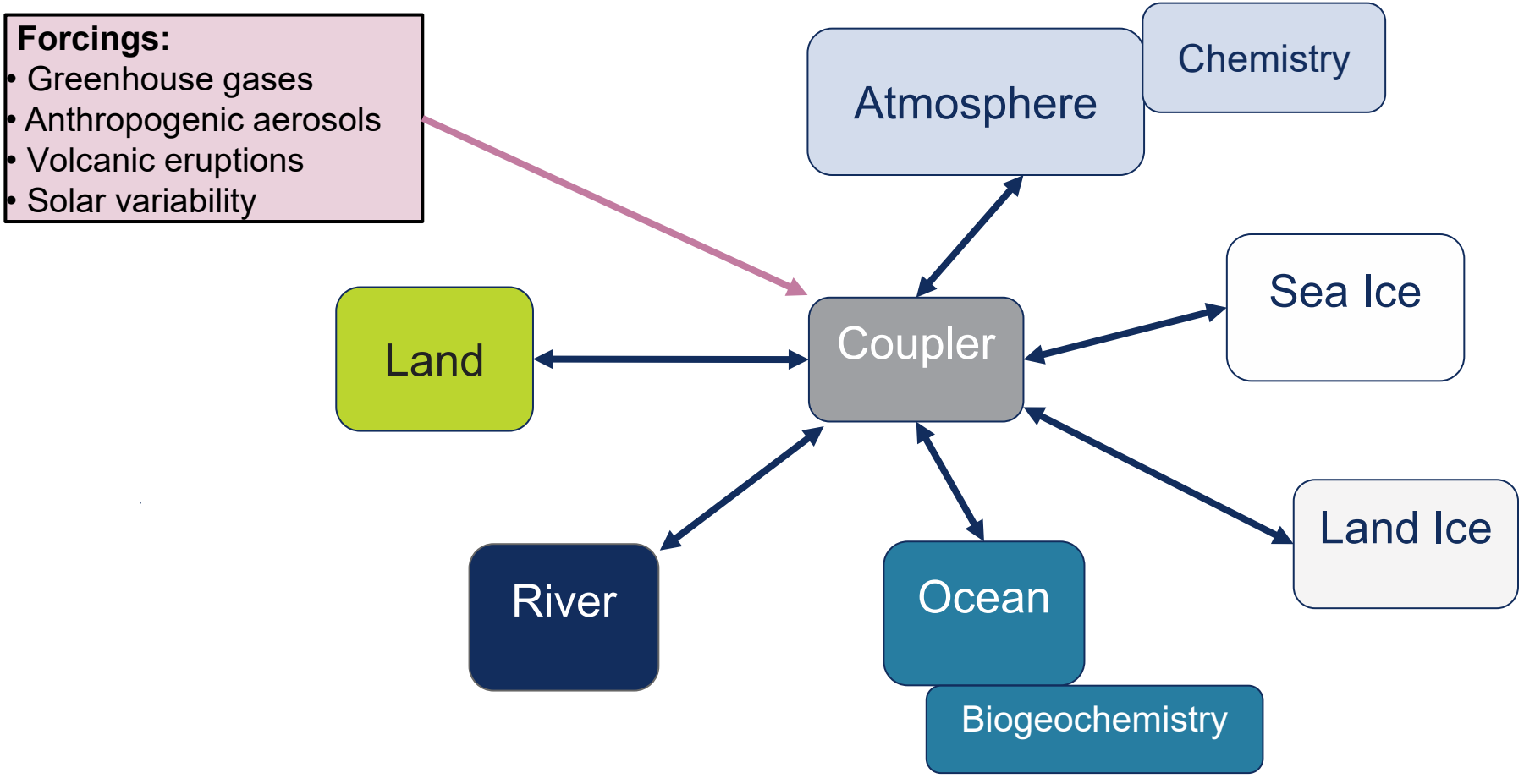


Global Earth System Models

- 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)



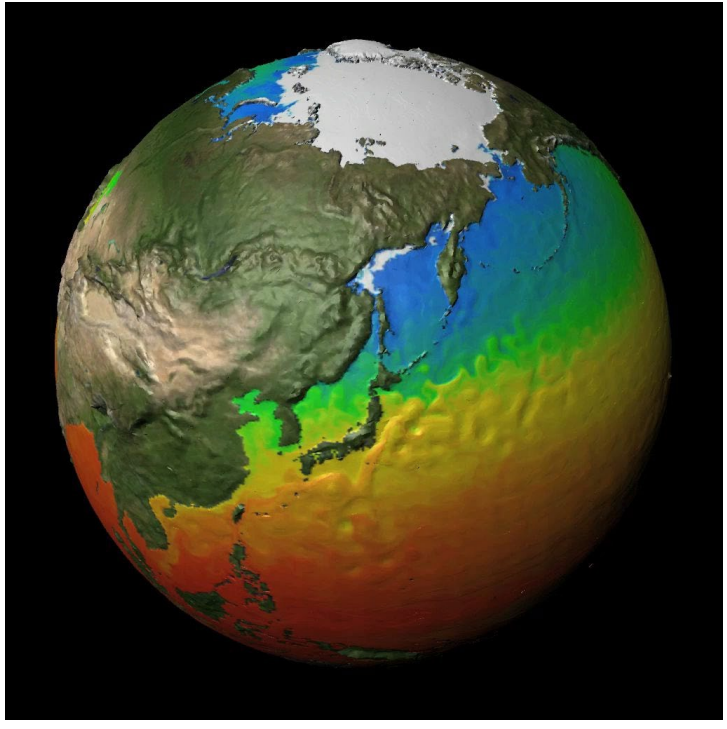
Structure of a fully coupled Earth System Model



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



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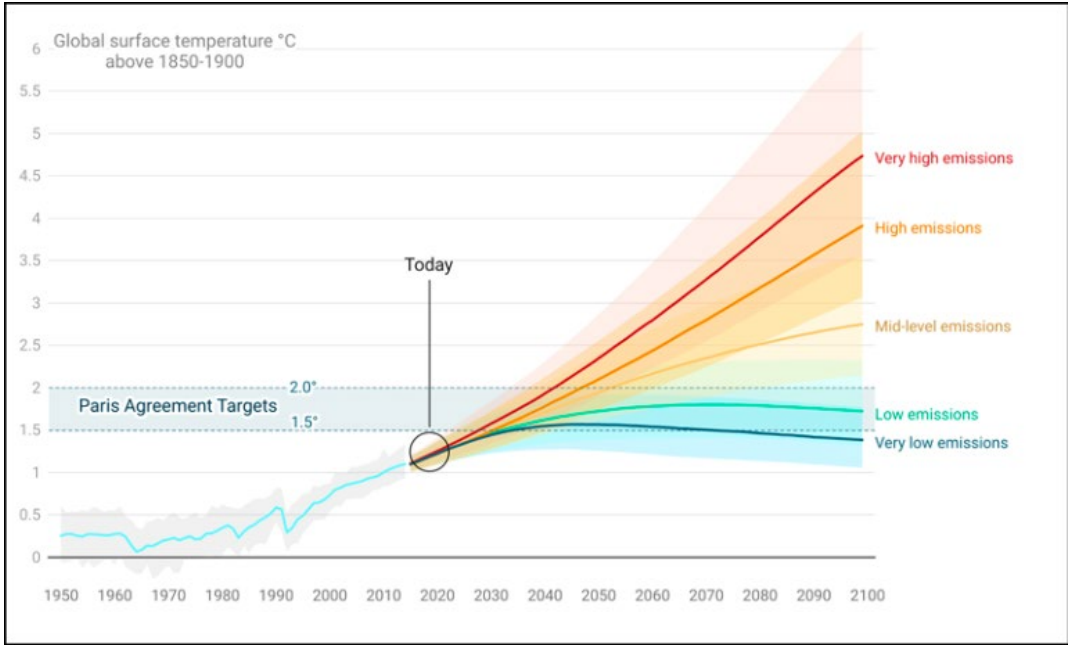
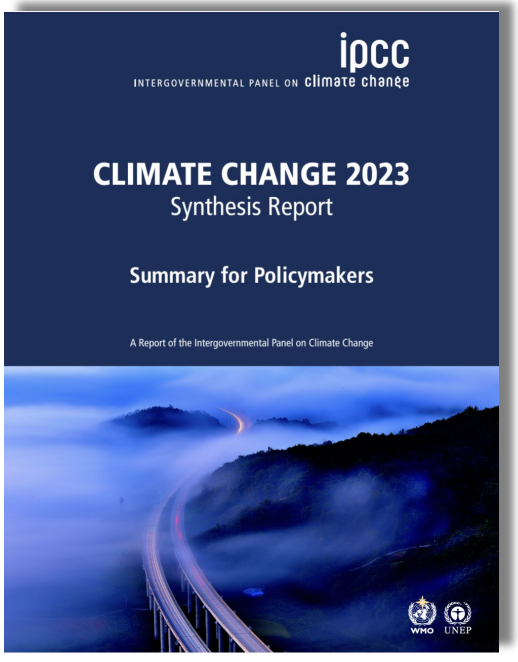
Output from Earth System Models is key basis for IPCC reports

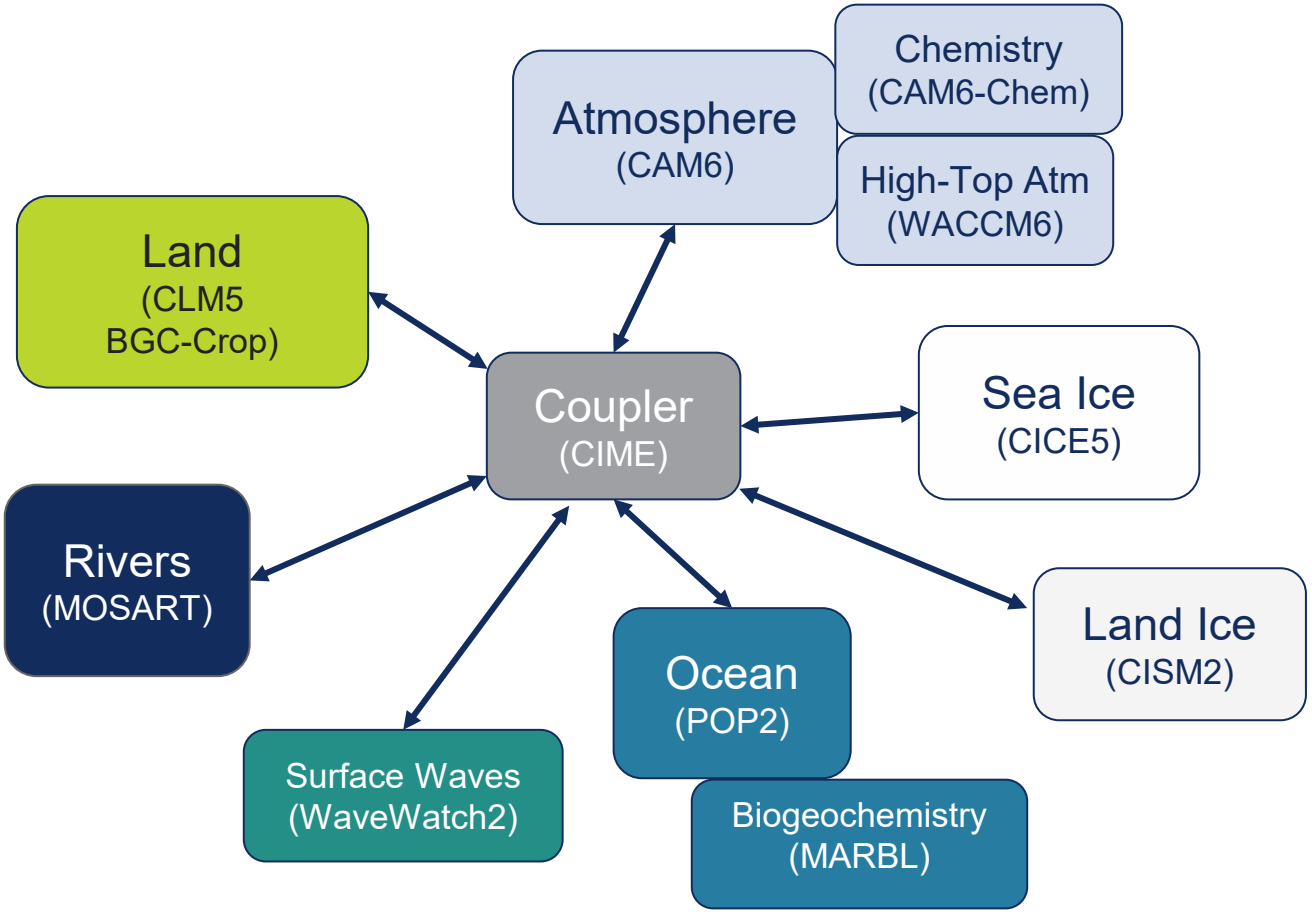




IPCC, AR6 Report

Community Earth System Model (CESM2)

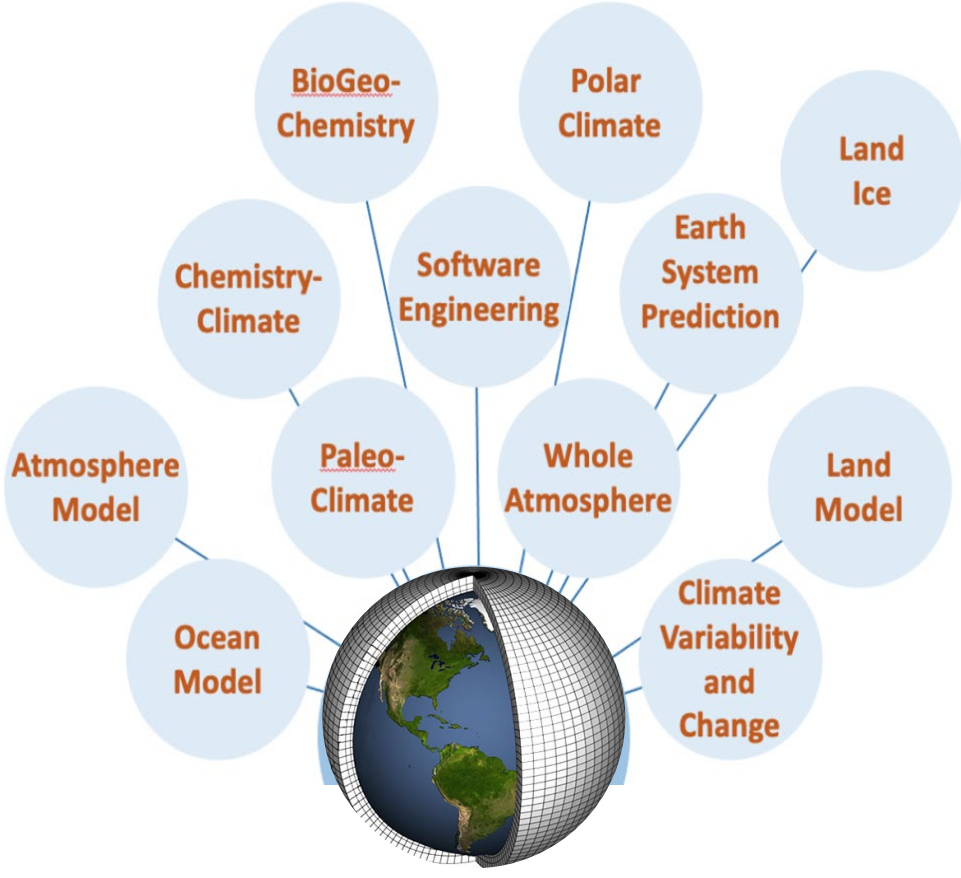
Model configuration used for simulations submitted to the Coupled Model Intercomparison Project (CMIP6) and many other community simulations (e.g., CESM2 Large Ensemble)



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., 400+ talks using CESM at AGU 2024
- 4.5 million lines of Fortran (!) code, >1000 geophysical variables

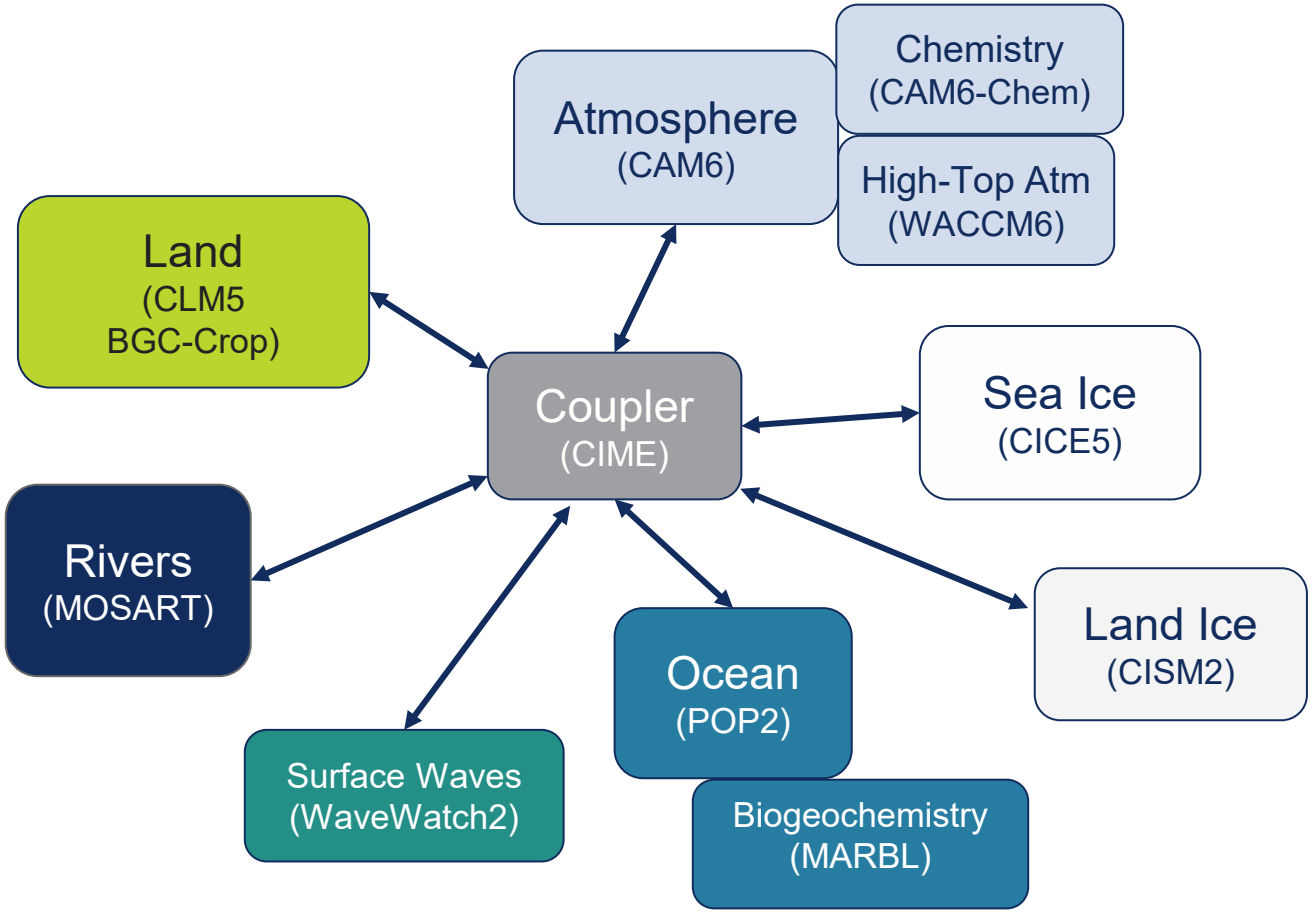


CESM is a virtual laboratory for the research community

Virtual laboratory to study

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

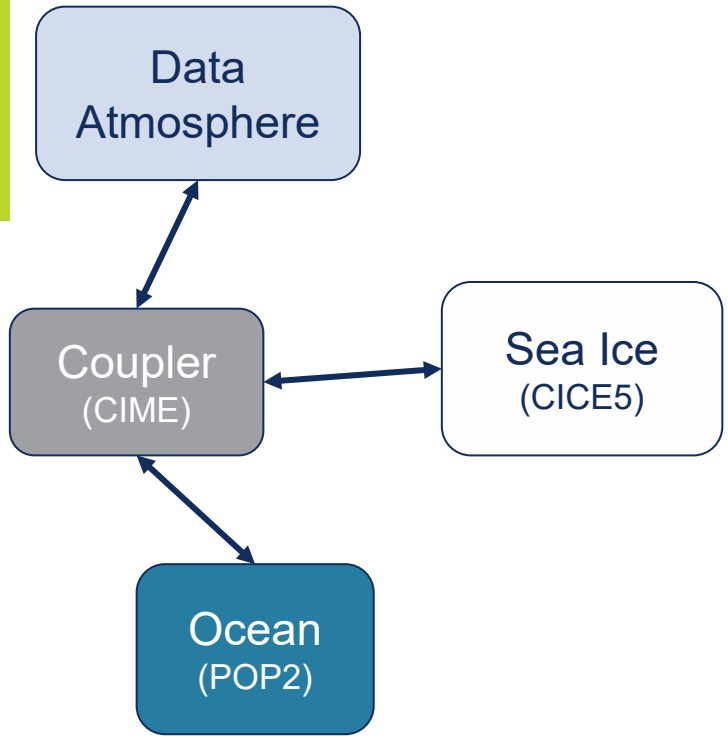
CESM supports a range of climate science research through a single model code base



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)



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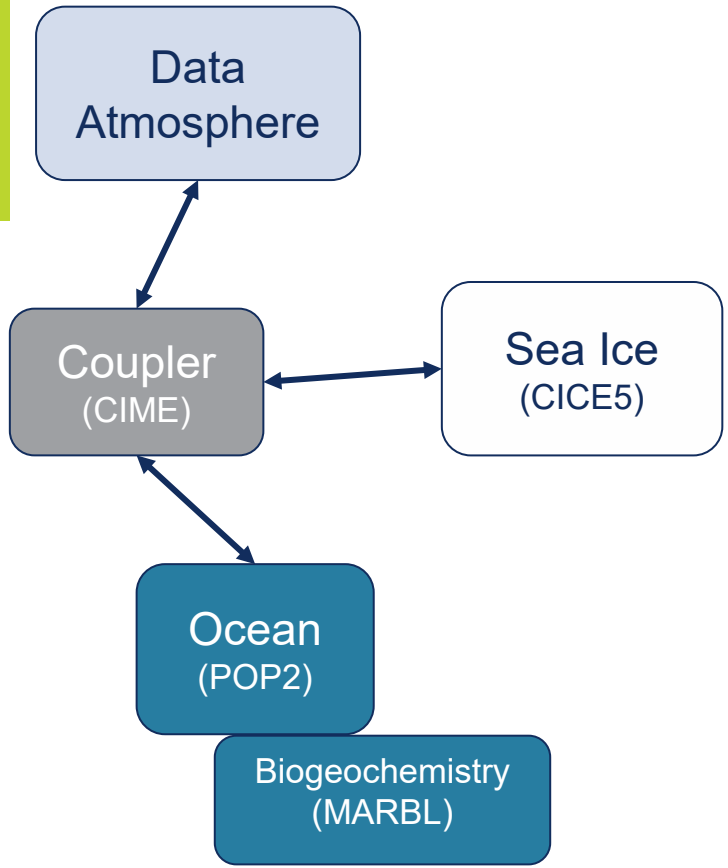

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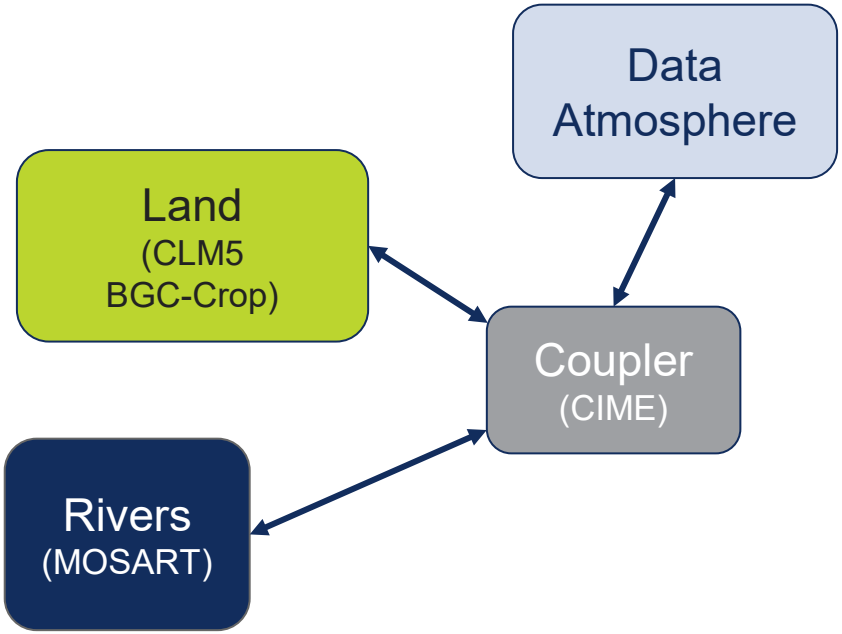
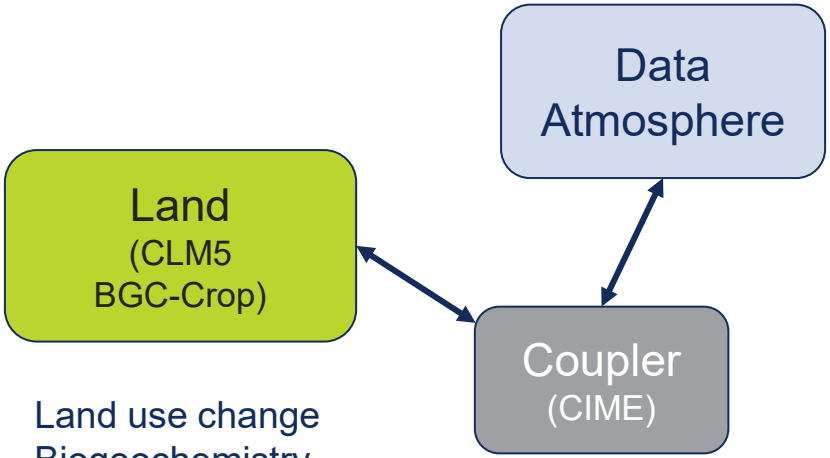
For example, you can turn on and turn off different components and replace them with a Data model



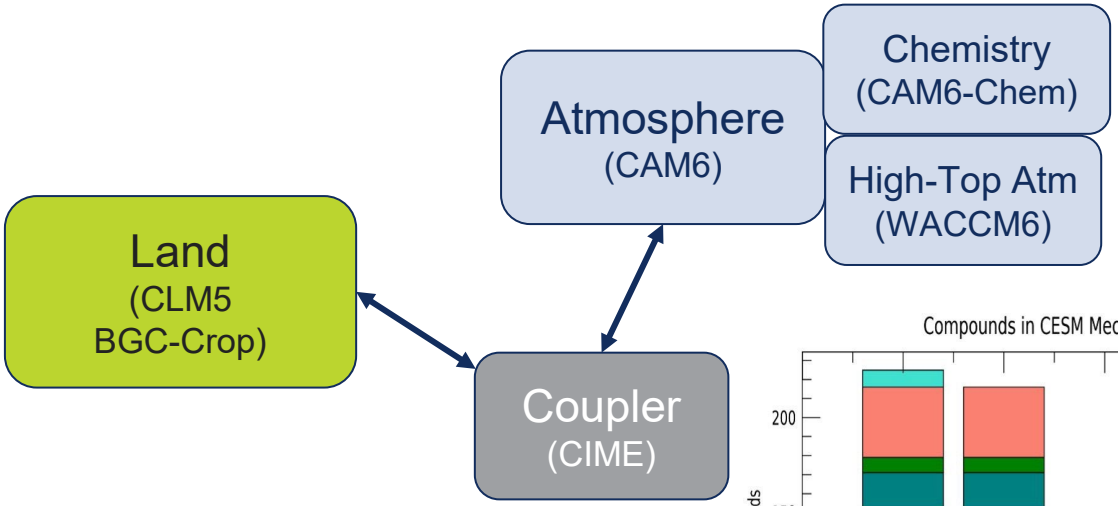
CESM supports a range of climate science research through a single model code base

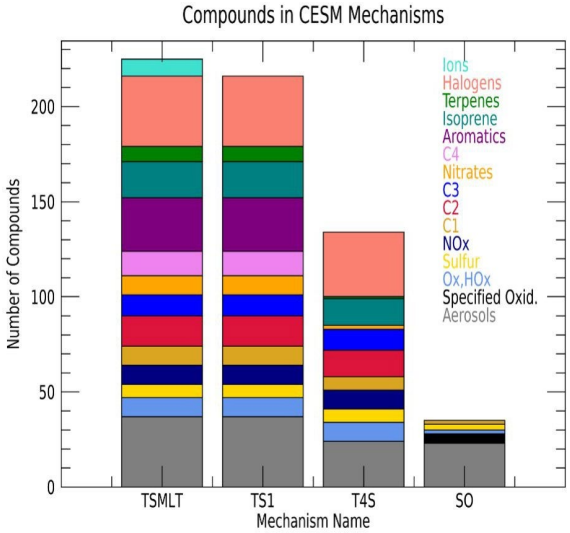
And, within each component model, there are many choices you can make about parameterizations, complexity levels, etc.



- 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





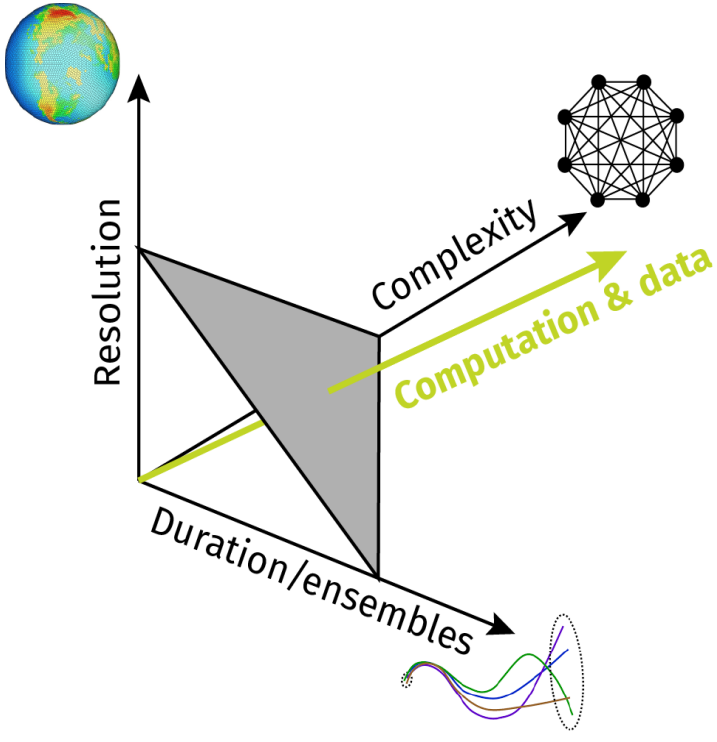
Earth System models and data can be a tool in your research toolbox

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

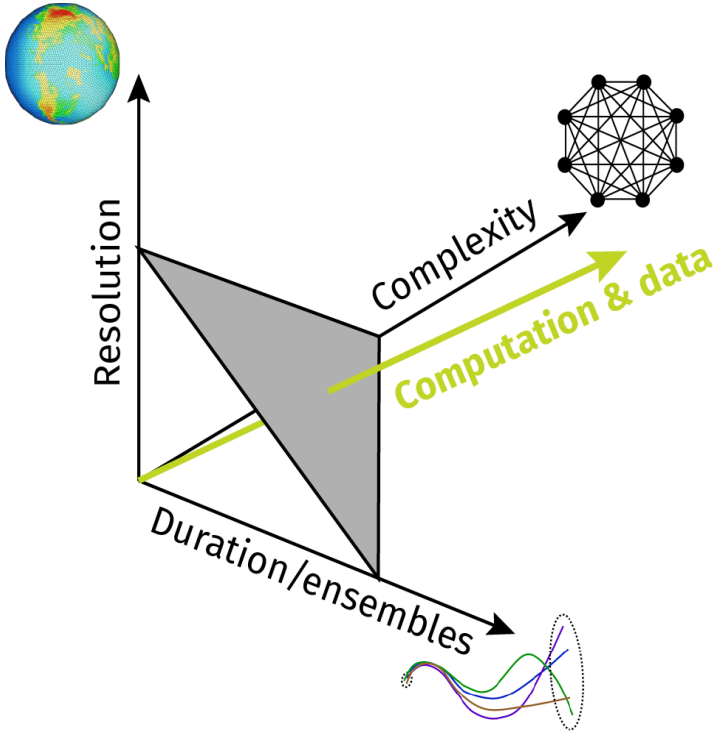
- **But, that's just the beginning …**
  - learning how to usefully apply ESMs and ESM data to answer research questions never ends
  - advice: be creative, acknowledge that there will be missteps, have fun!

Earth System Modelling is hard!

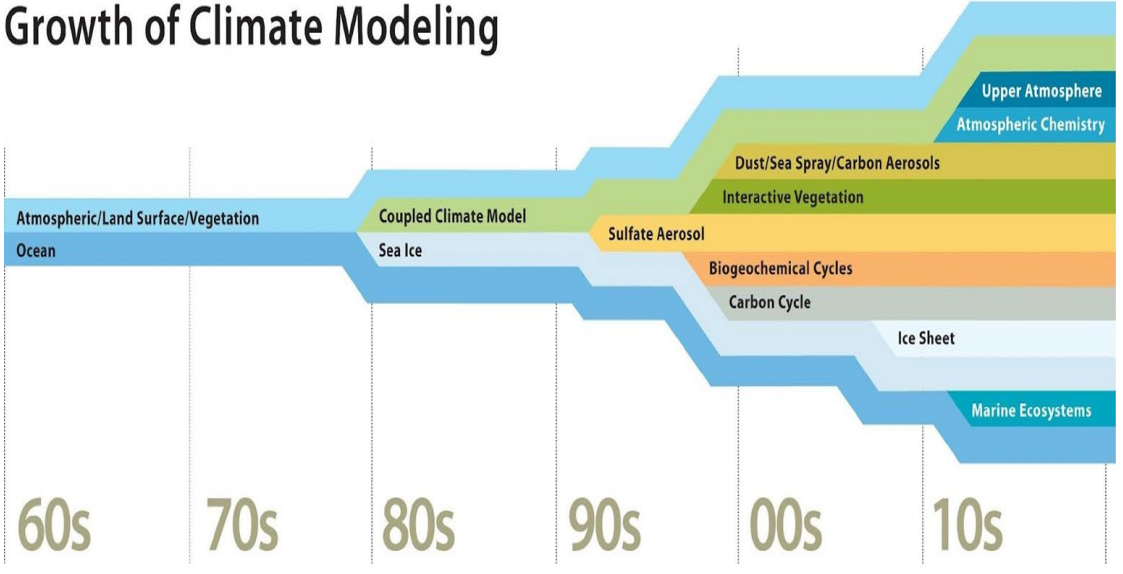
Different research questions require different considerations



Different research questions require different considerations



Complexity



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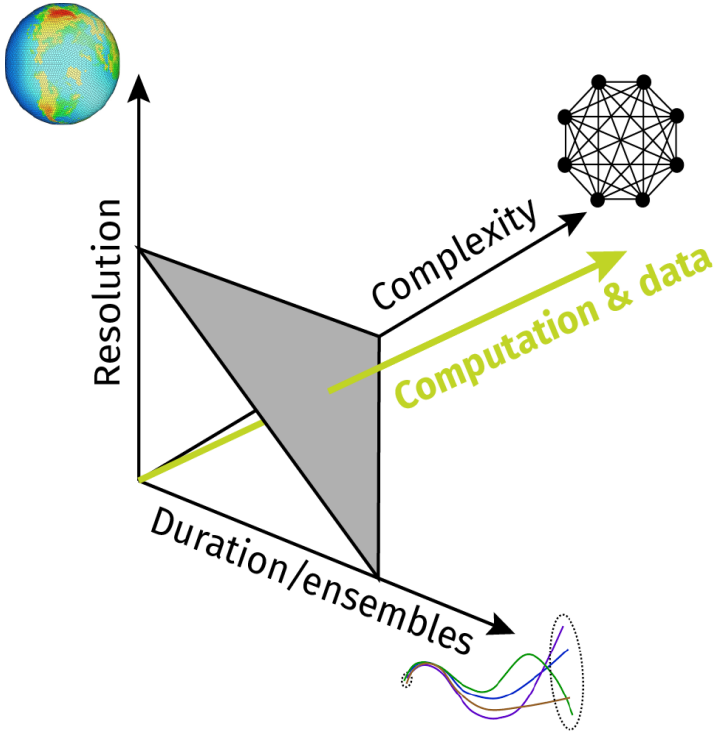
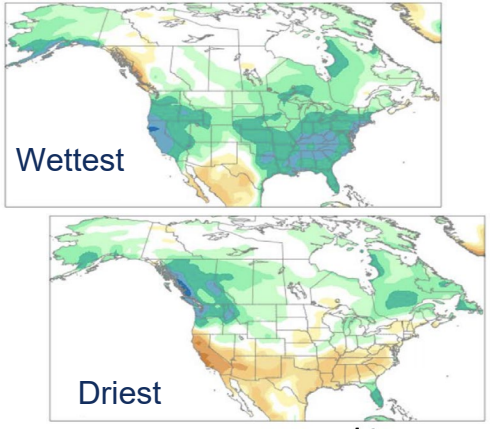
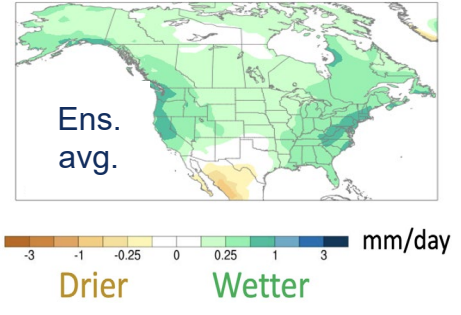


Large ensembles
climate change uncertainty

Internal vs Forced



Winter Precipitation Trend
(2010-2060)



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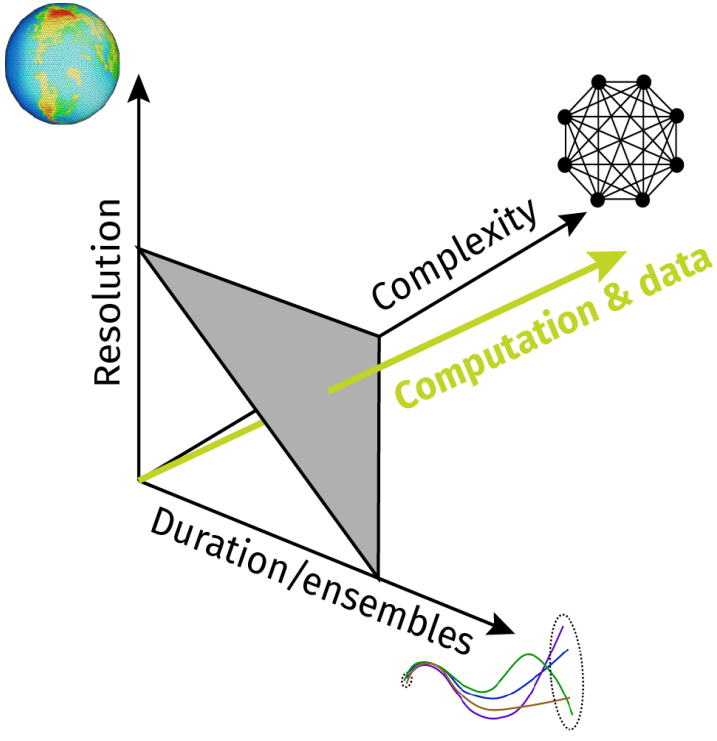
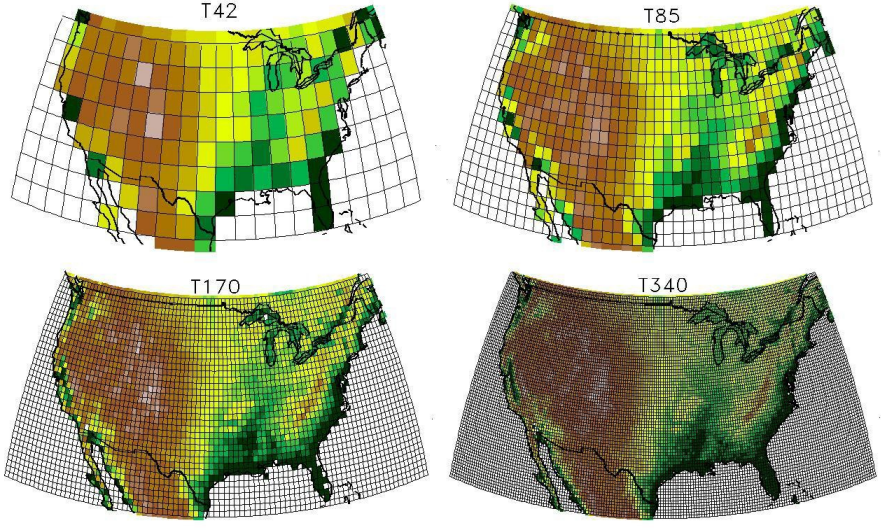
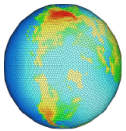


Resolution



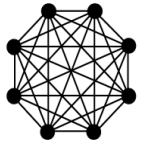
Providing Data for the Community, Including for AI Training

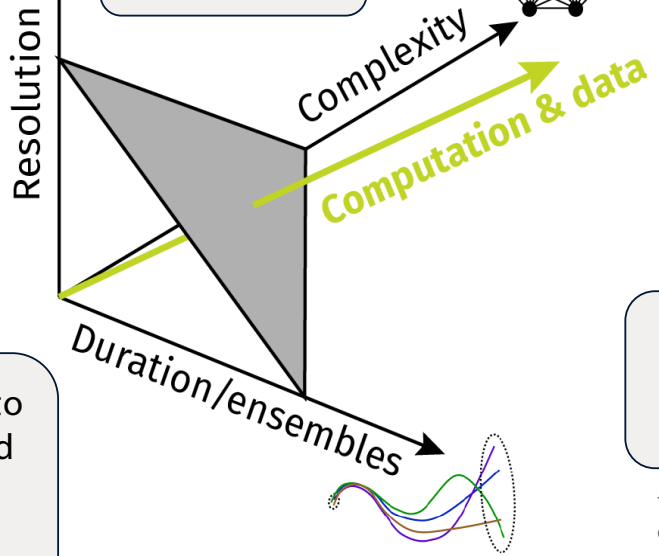
CESM Simulation Data
20+ PBs
1000's of geophysical variables at hourly, daily, monthly timescales



New
MESACLIP
Citations: >300

New
DYAMOND





CMIP5, CMIP6
Citations: Many thousands

Large Ensembles
(CESM1, CESM2)
Citations: >3200

Last Millennium Ensemble
Citations: >600

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

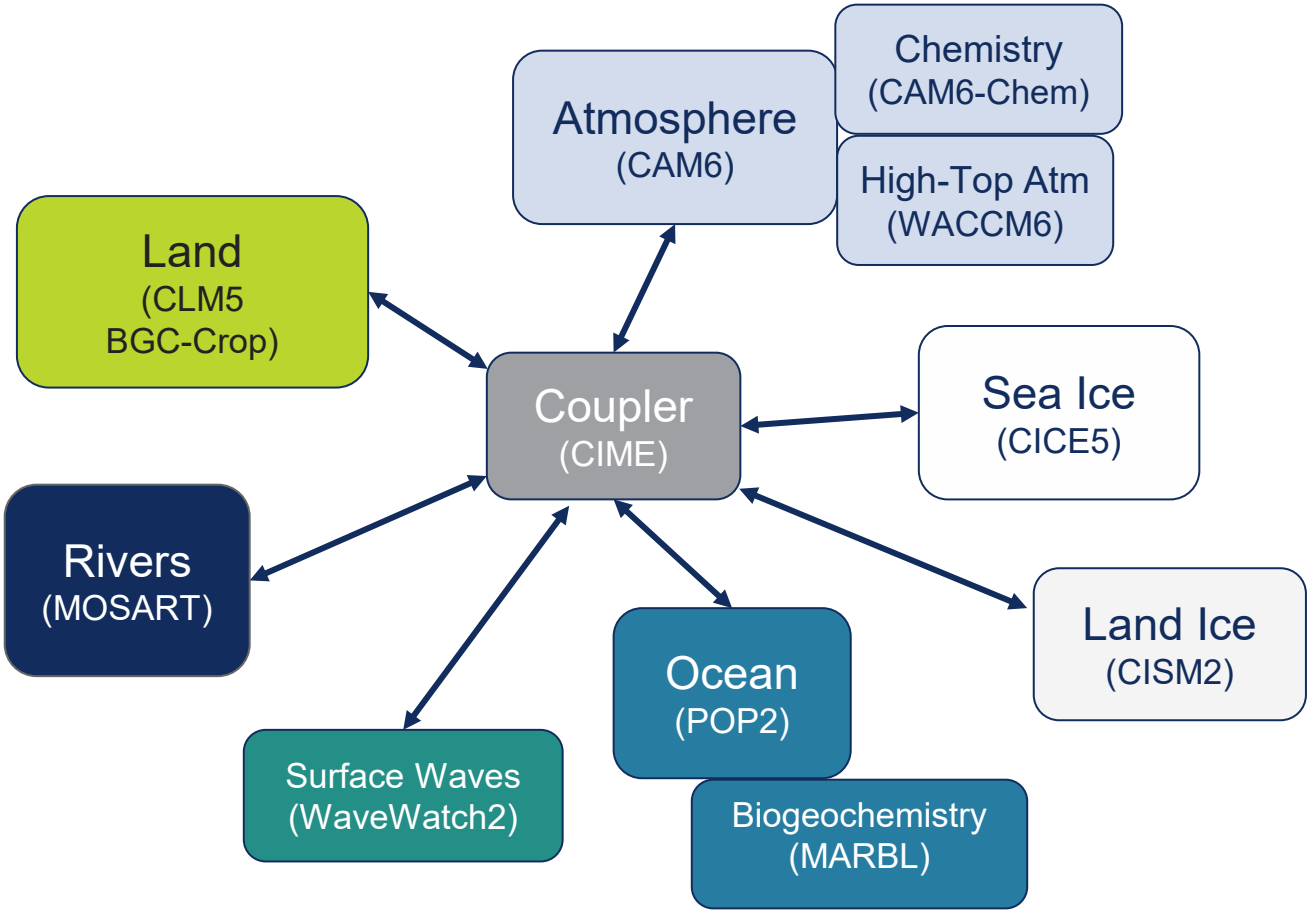
*The datasets here are a non-comprehensive subset of published simulation datasets

GDEX

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

Community Earth System Model (CESM2)

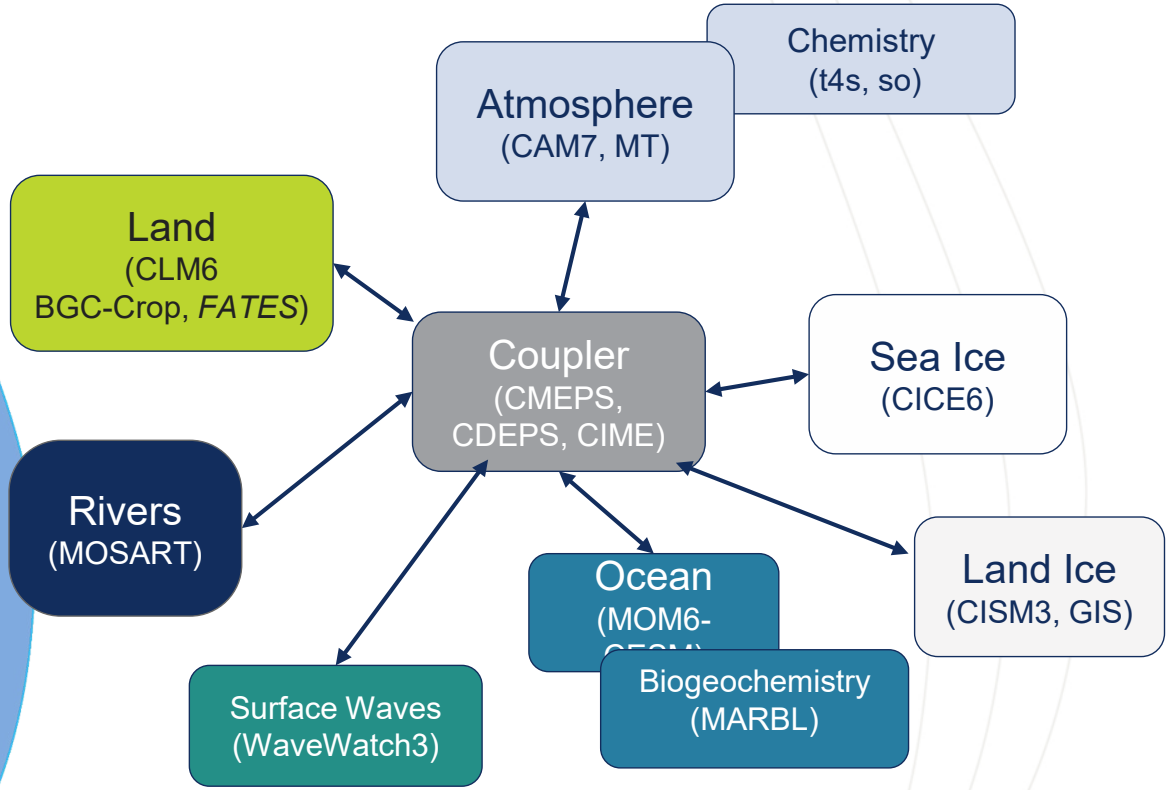
Model configuration used for simulations submitted to the Coupled Model Intercomparison Project (CMIP6) and many other community simulations (e.g., CESM2 Large Ensemble)



Community Earth System Model (CESM3)

Major upgrades to CESM2

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



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, ….

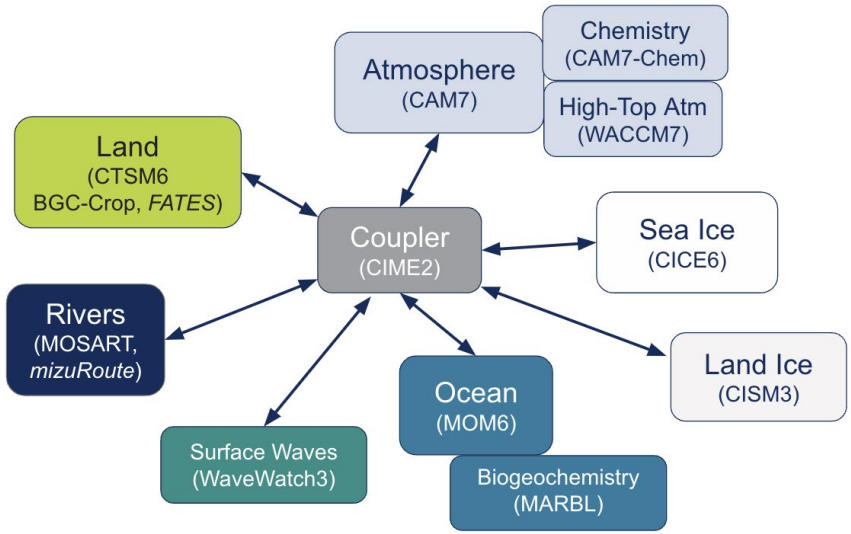
Ocean: MOM6, hybrid coordinate, variable sea level, tracer budgets within the Lab Sea, stochastic GME, isopycnal diffusion (Redi), …

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, …



Forces driving the future of Earth System modeling

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

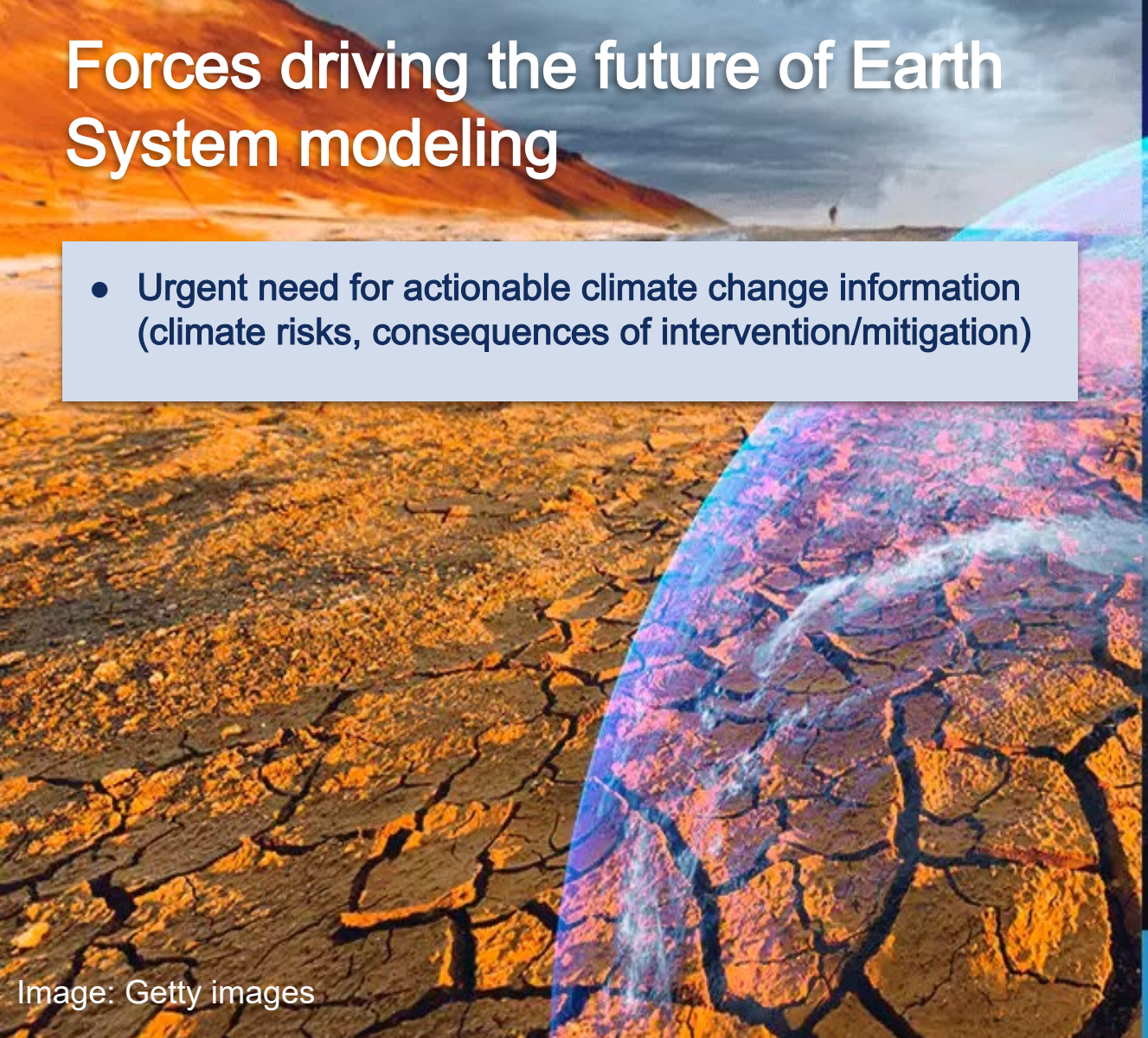


Image: Getty images

Image: NOAA; www.noaa.gov/education/resource-collections/climate/climate-change-impacts

Forces that are driving the future of Earth System modeling

Evolving needs

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

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

Science Advances

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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

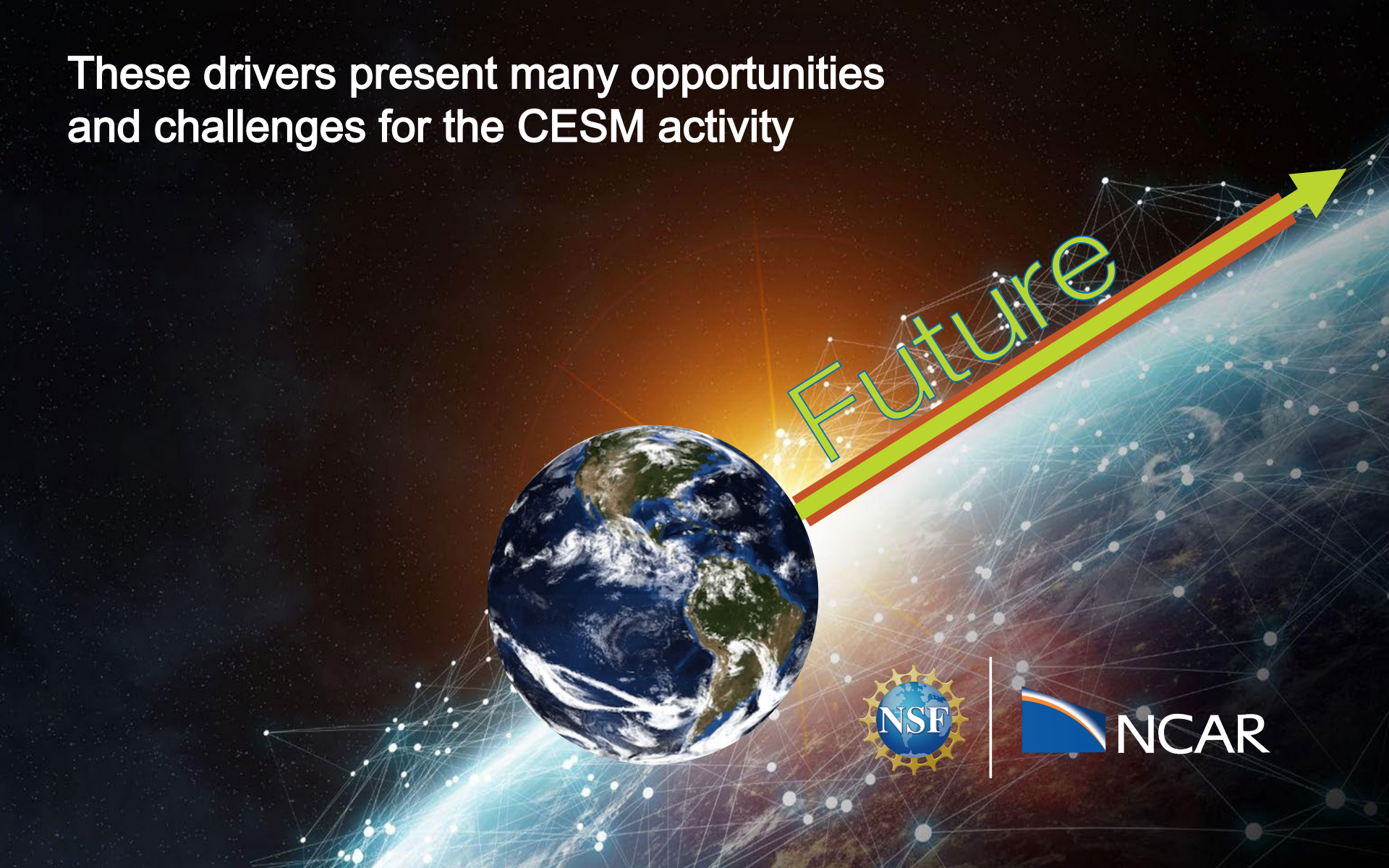
Image: Getty images

Forces that are driving the future of Earth System modeling

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

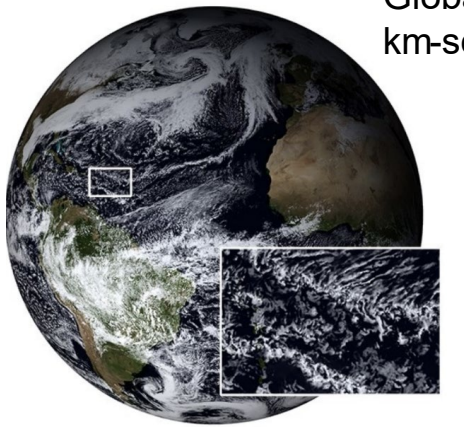
Image: Getty images

These drivers present many opportunities and challenges for the CESM activity

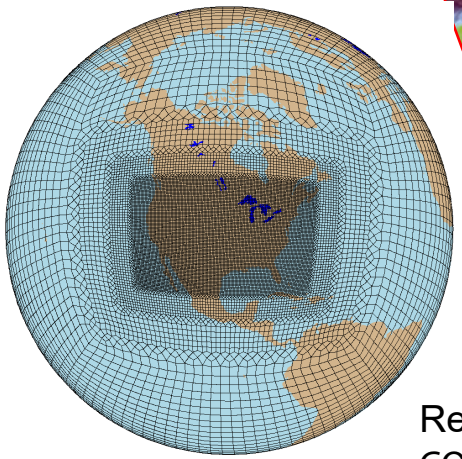


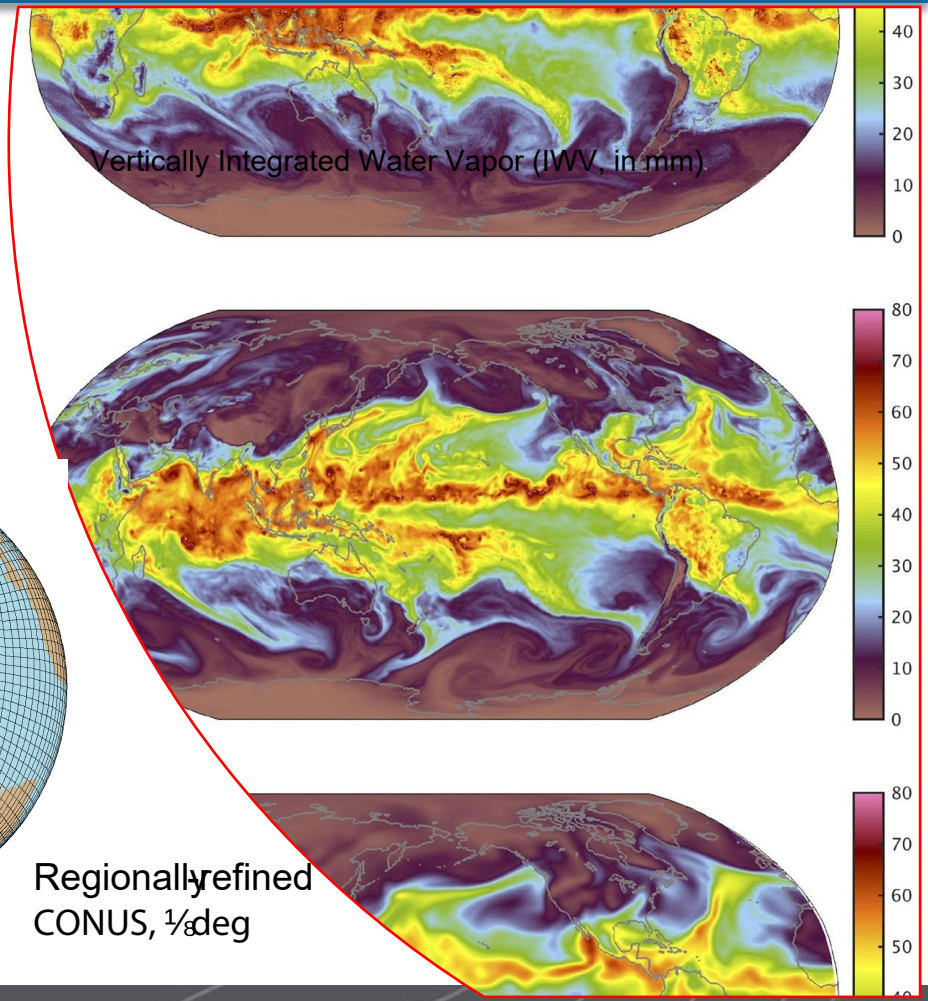
CESM high-resolution progress and plans

- CESM1.3(HR): 0.25° atm/lnd, 0.1° ocn
- Developing CESM3 HR version
- CESM EarthWorks and STORMspeed projects developing km-scale configuration
- Several regionally-refined grids available



Global
km-scale





Regionally-refined
CONUS, ⅛deg

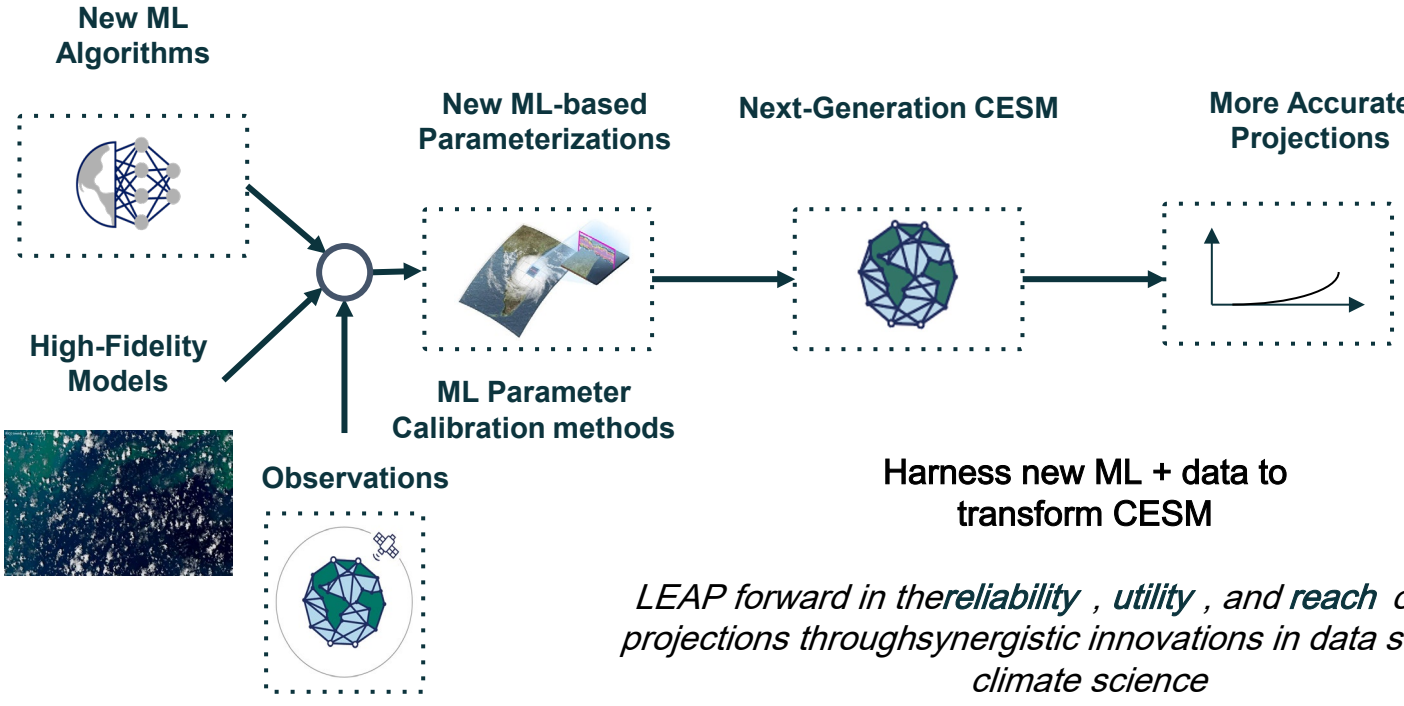
Chang et al. (2020, JAMES)

Towards a hybrid (physics + Machine Learning) version of CESM (CESM3MLe)

LEAP

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

M²LInES
Schmidt Futures



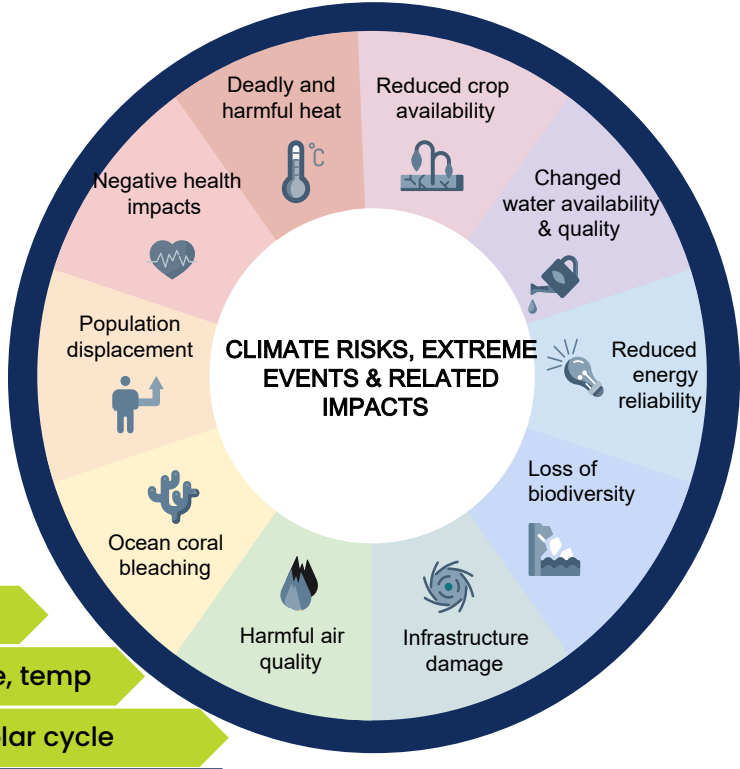
Harness new ML + data to transform CESM

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

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

Guided by societal needs, spanning minutes to centuries

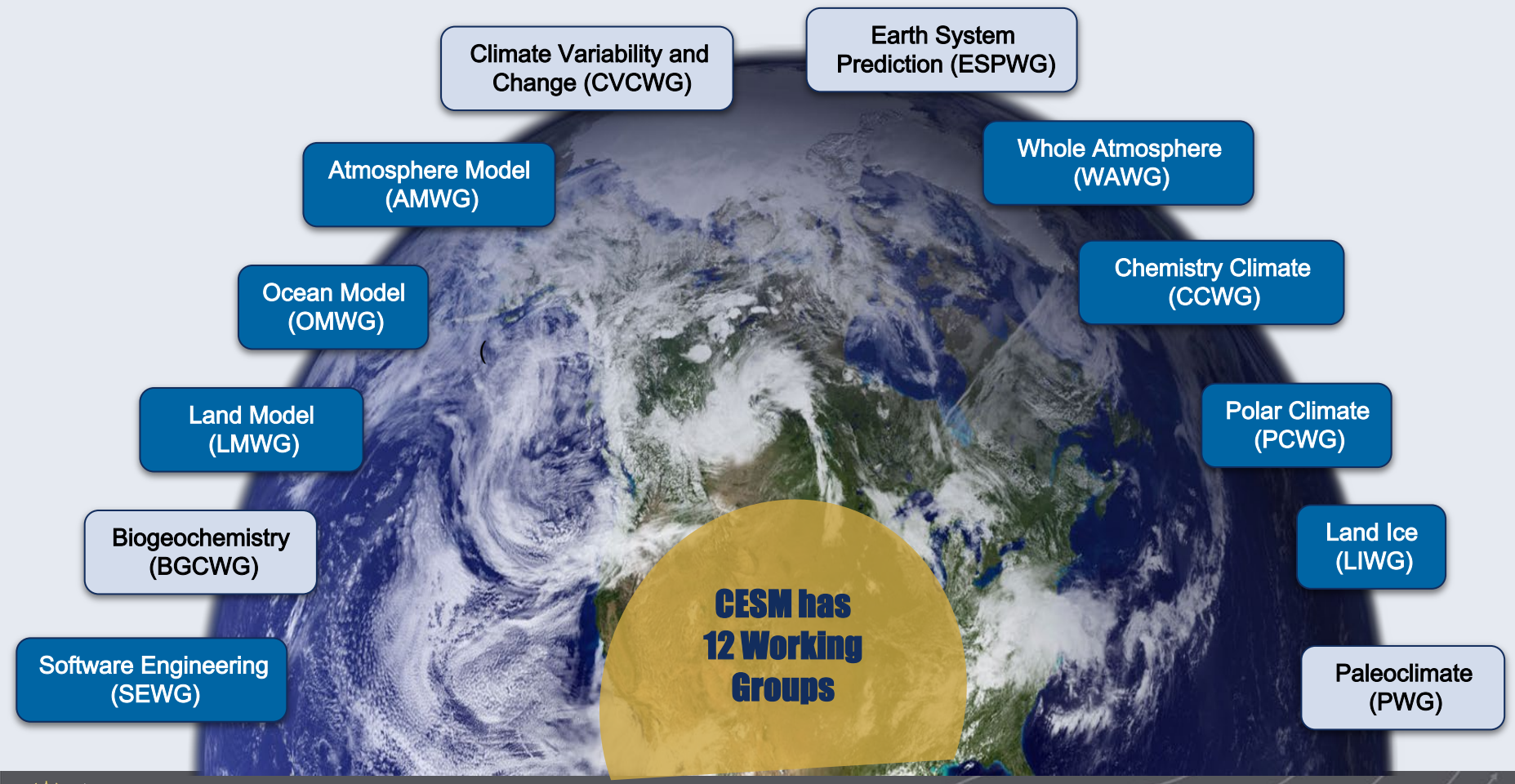
- Tornadoes
- Flooding
- Solar Flares/CME
- Storm Surge
- Wildfires
- Air Quality
- Solar Rossby Waves
- Heat/Cold Waves
- Drought/floods
- Seasonal Temp & Precip
- Sea-ice, land-ice
- Sea-level rise, temp
- Solar cycle



Minutes → Centuries

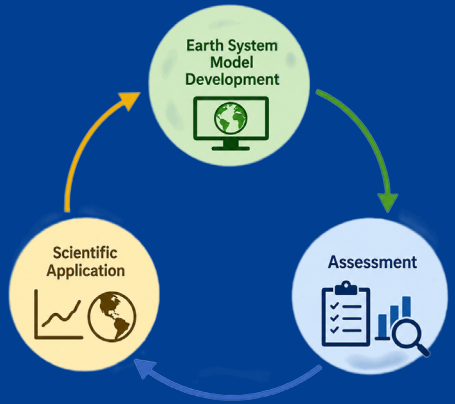
NSF NCAR working with research community to define near- and long-term priorities

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 thr

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)

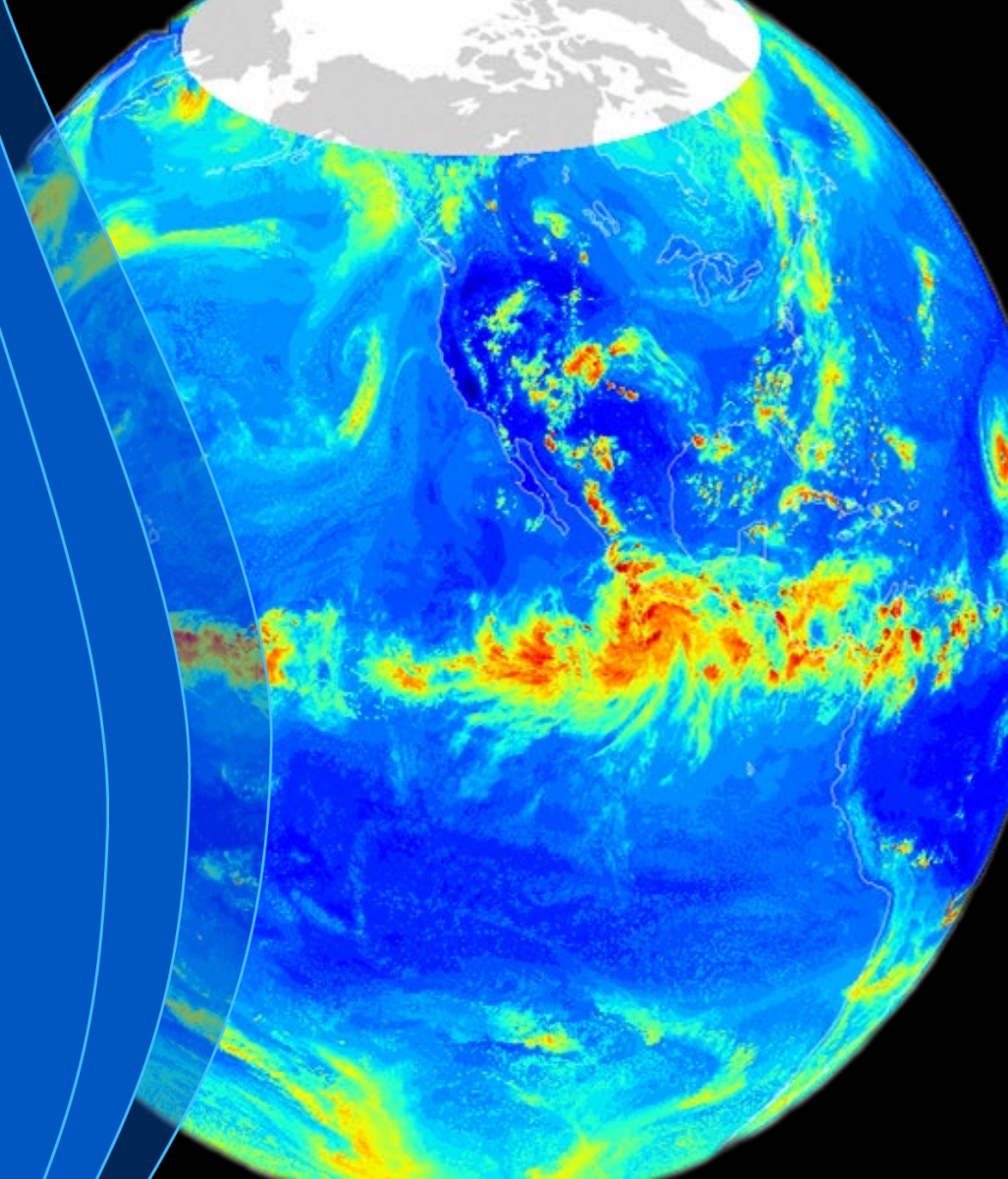
32nd Annual CESM Workshop (June 14 - 16, 2027)

31st Annual Workshop

210+ presentations from 150 unique institutions

NCAR
OPERATED BY UCAR

Thanks and Welcome to the CESM Community



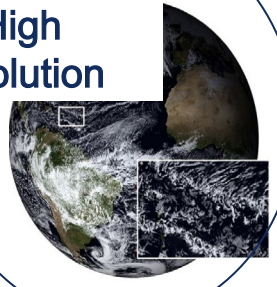
Unified modeling framework

“Pick and Choose” menu of options

–

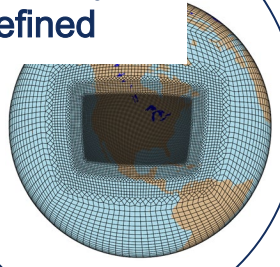
All components interact and are ready to play

Global High Resolution

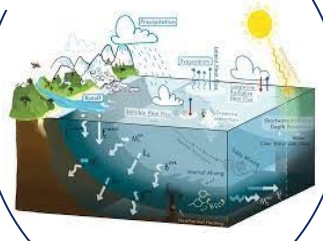


Global Low Resolution

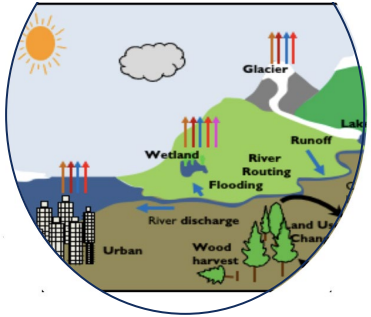
Regionally - refined



Ocean



Land / Hydrology



Chemistry

Space Weather