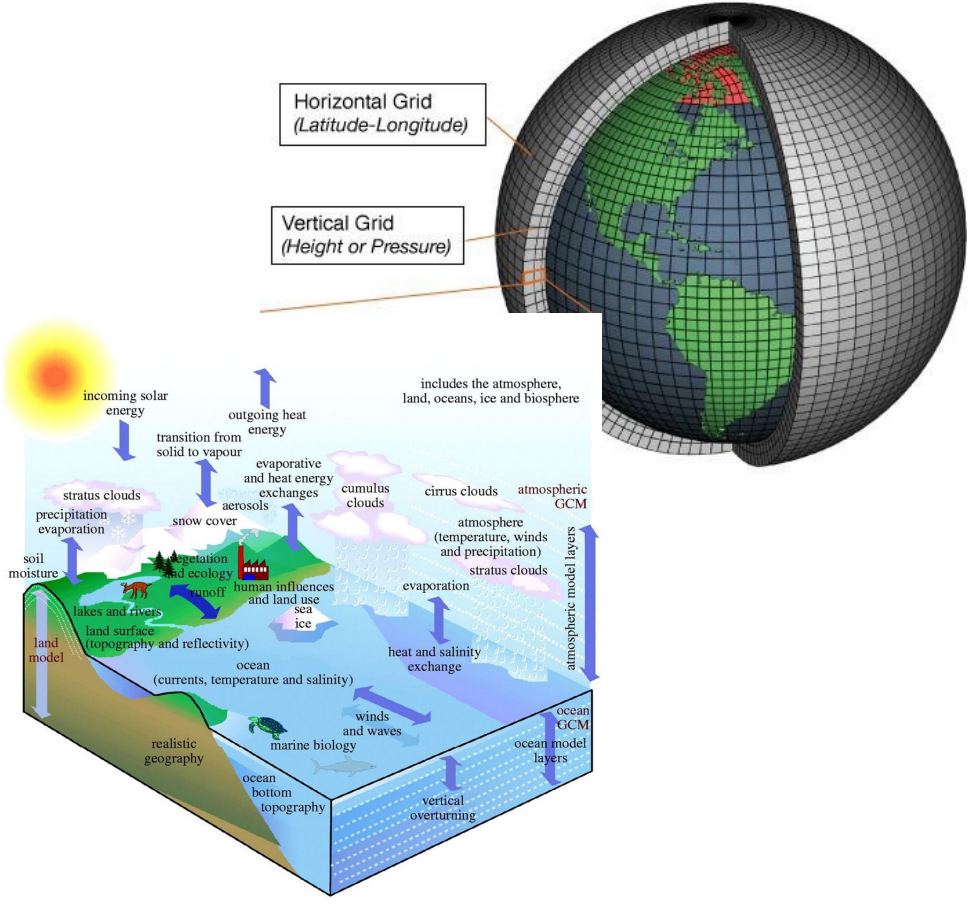
Introduction to the Community Earth System Model (CESM)

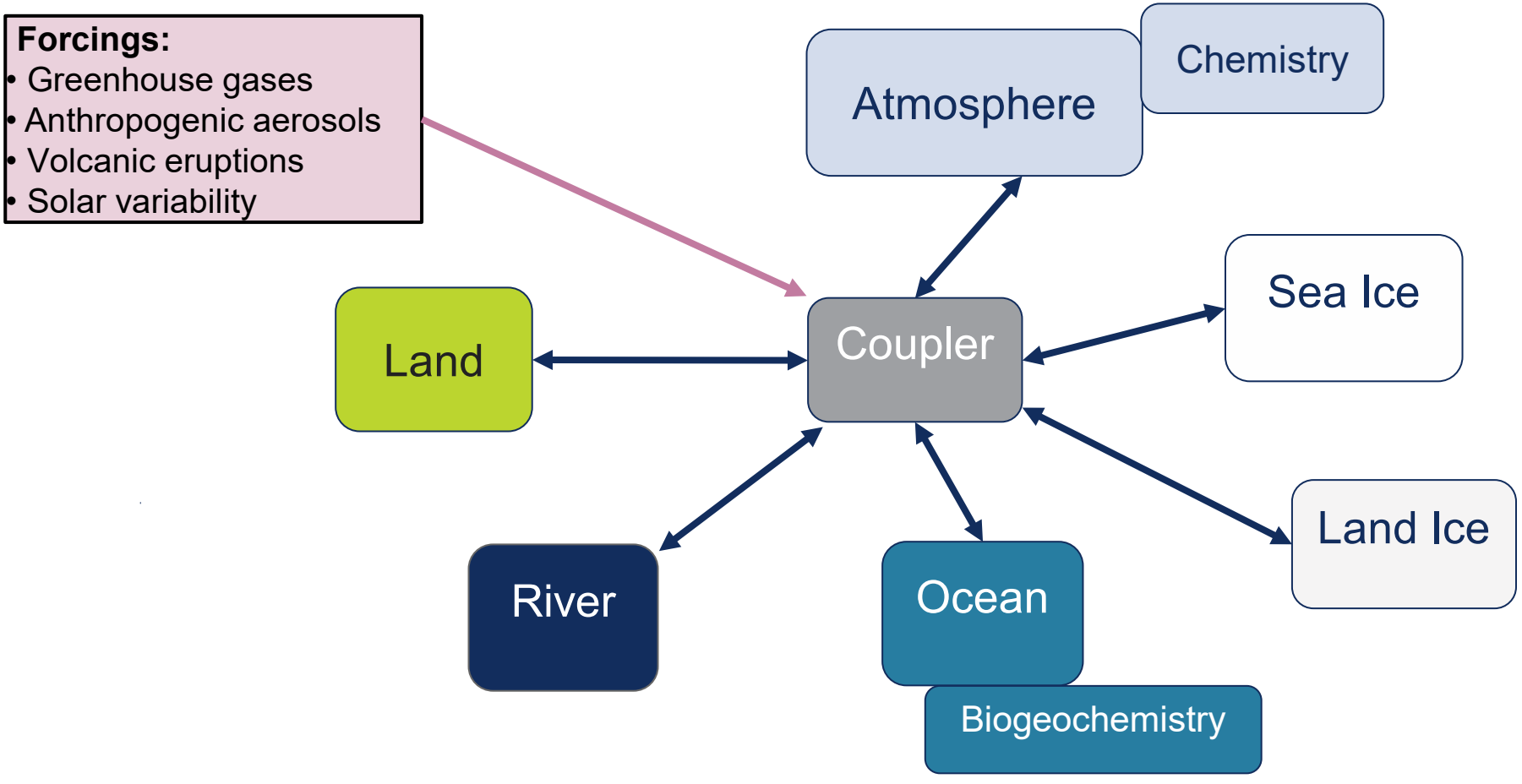
David Lawrence
CESM Chief Scientist

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)



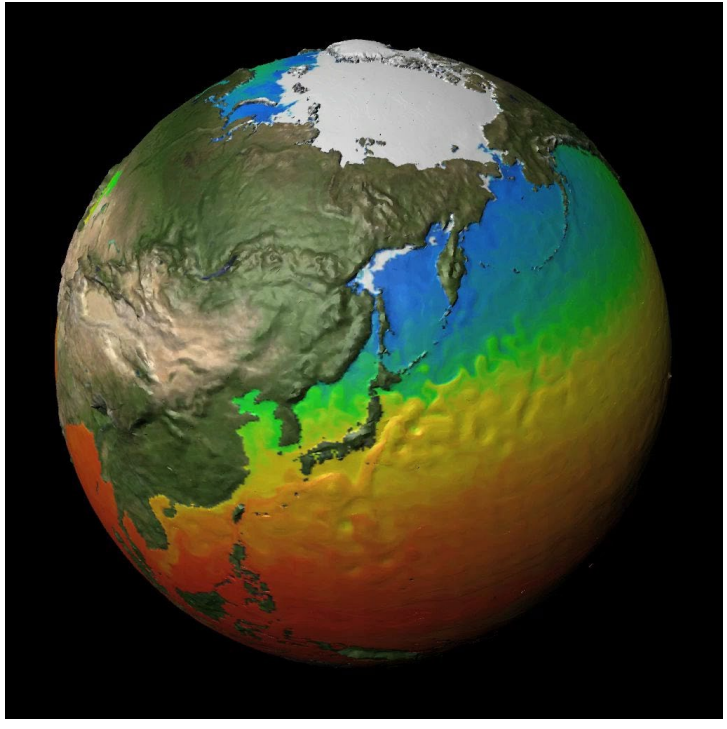
Structure of a fully coupled Earth System Model



Global Earth System Models

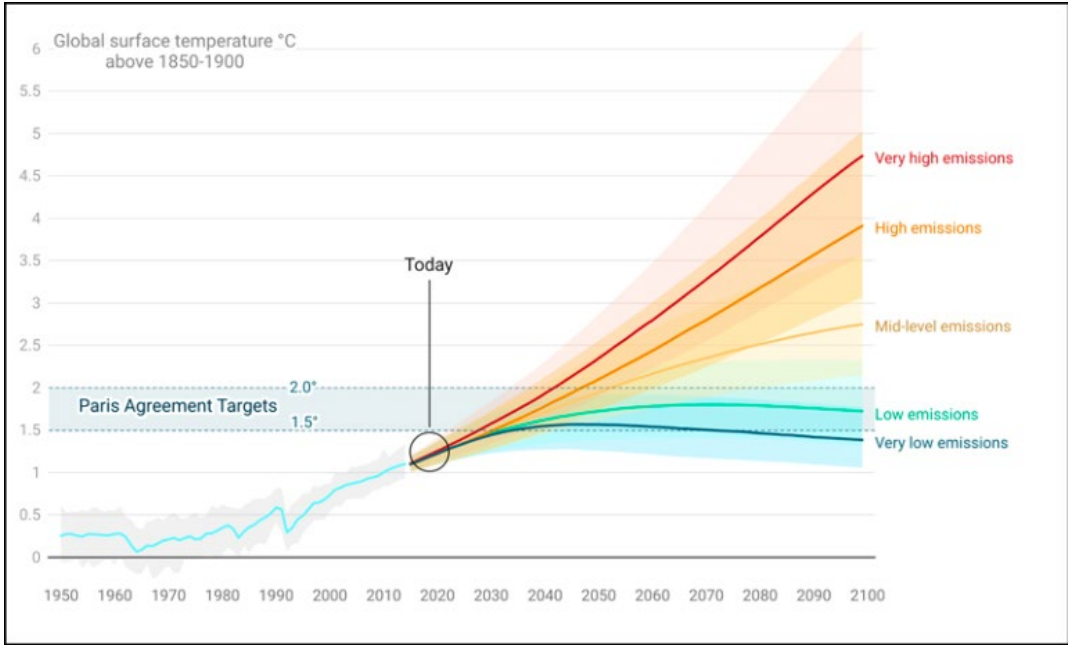
Many purposes, including:

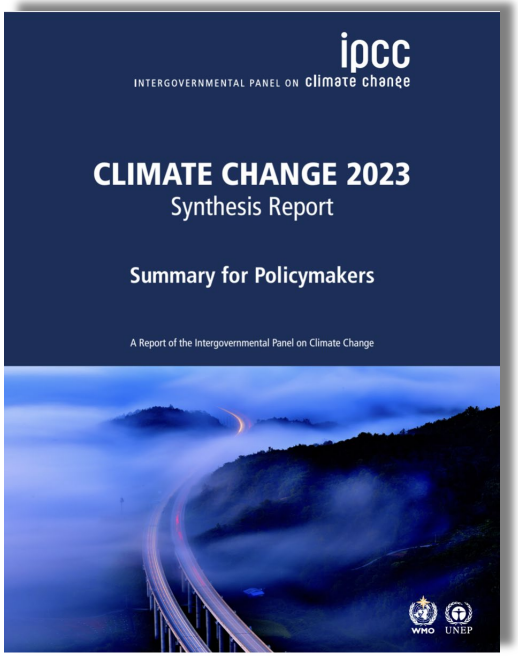
- Scientific and mechanistic understanding of past observed events and changes
- Studying recent past, present, and future (projections) climate changes and their impacts
- Studying climate variability
- Subseasonal-to-multidecadal Earth system predictions
- Providing actionable, societally-relevant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



Small and Scheitlin

Output from Earth System Models is key basis for IPCC reports

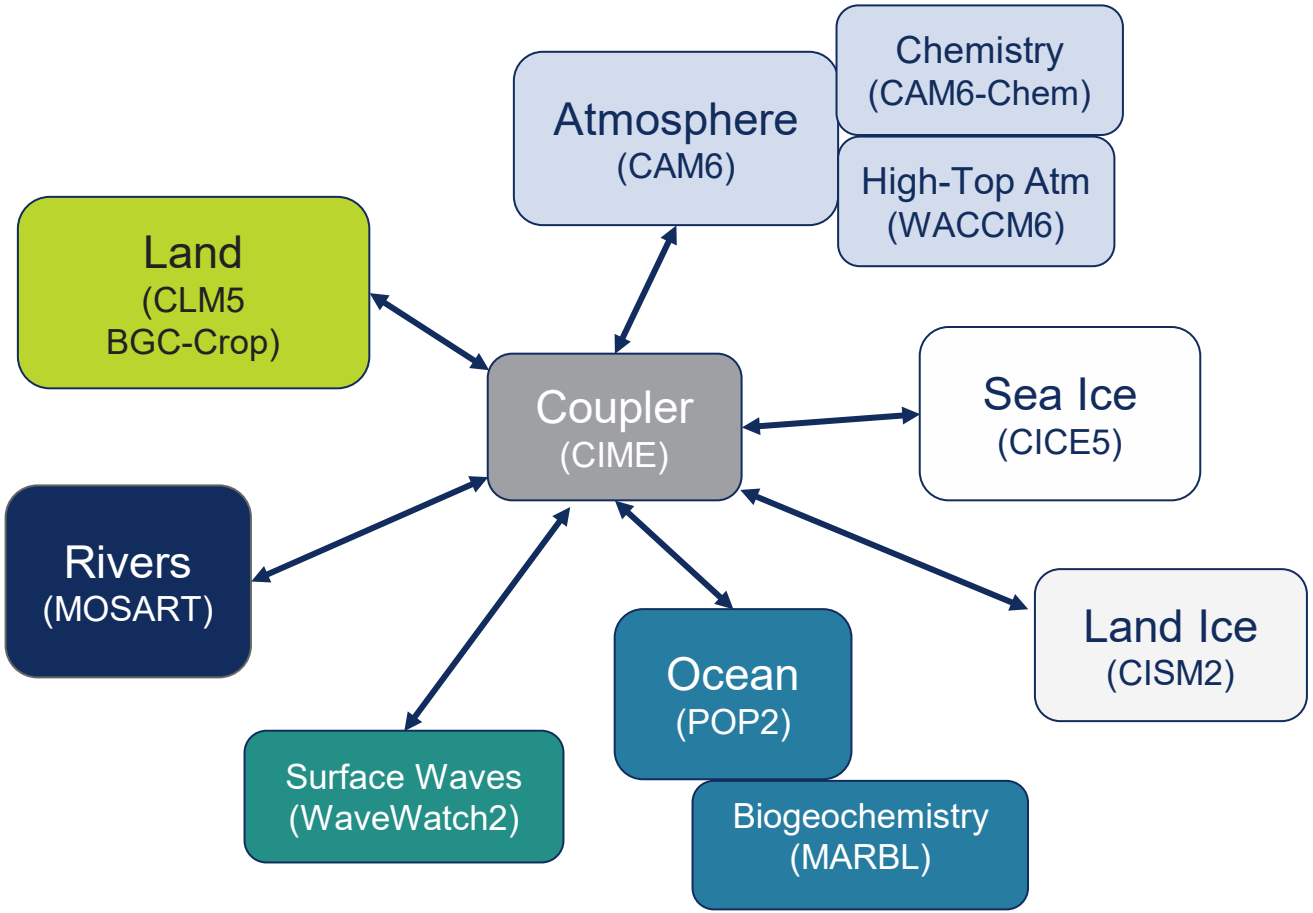




IPCC, AR6 Report

Community Earth System Model (CESM2)

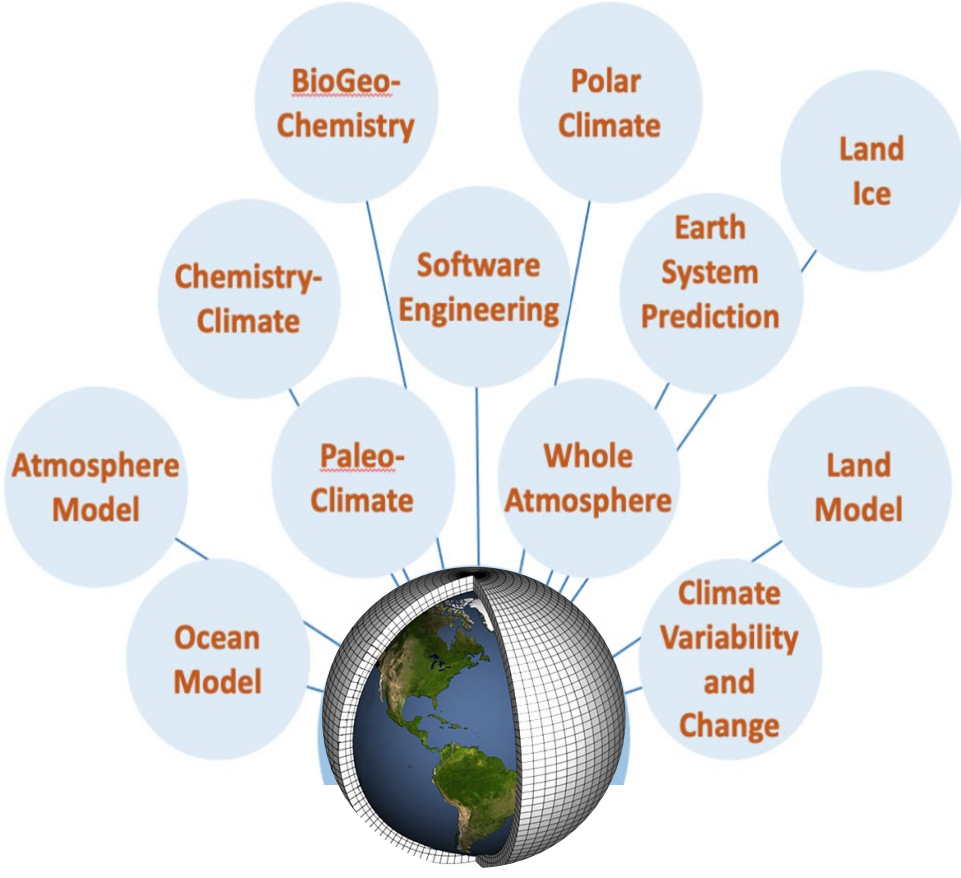
Model configuration used for simulations submitted to the Coupled Model Intercomparison Project (CMIP6) and IPCC AR6 many other community simulations (e.g., CESM2 Large Ensemble)



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
- 2.8 million lines of Fortran (!) code, >1000 geophysical variables

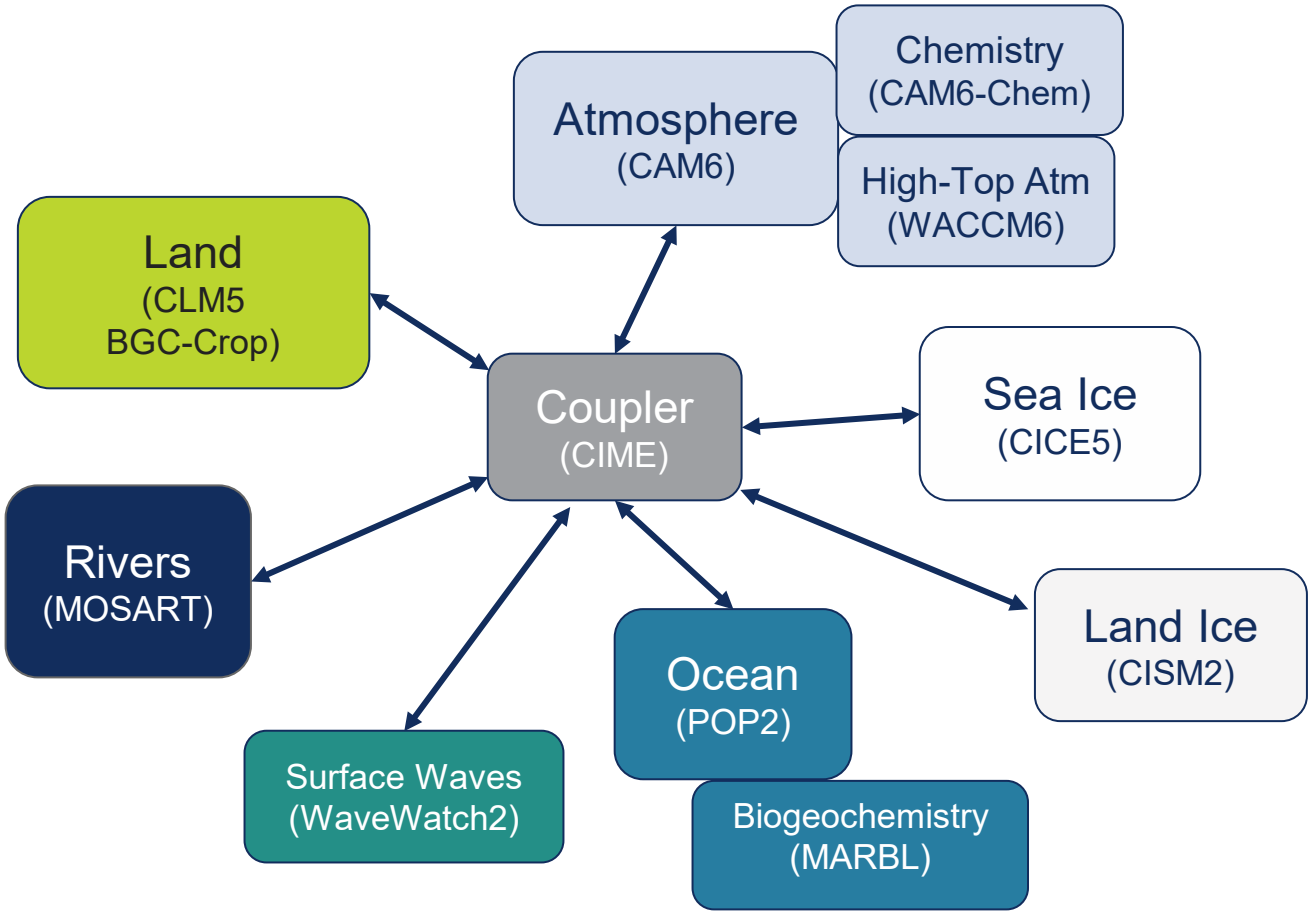


CESM is a virtual laboratory for the research community

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
- ...

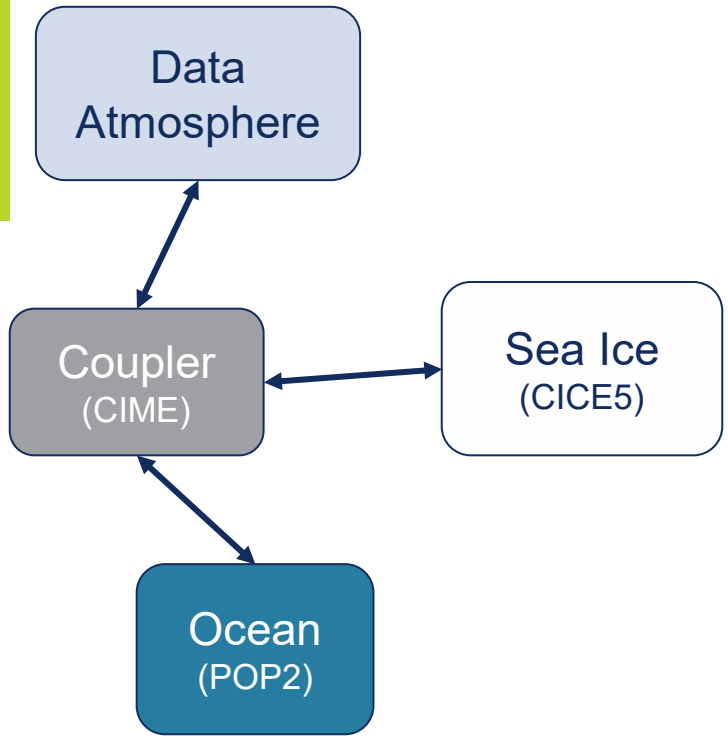
CESM supports a range of climate science research through a single model code base



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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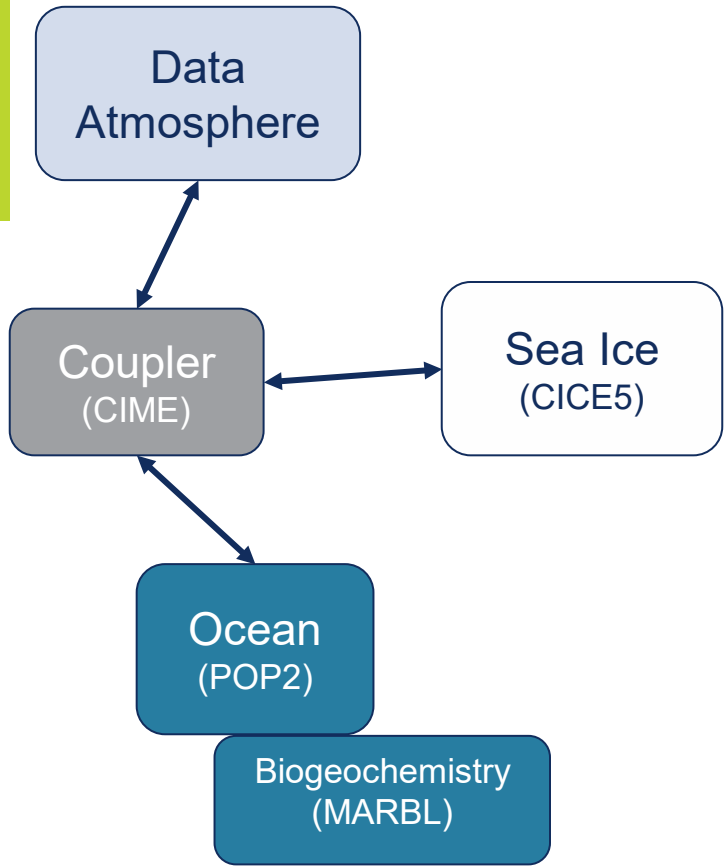

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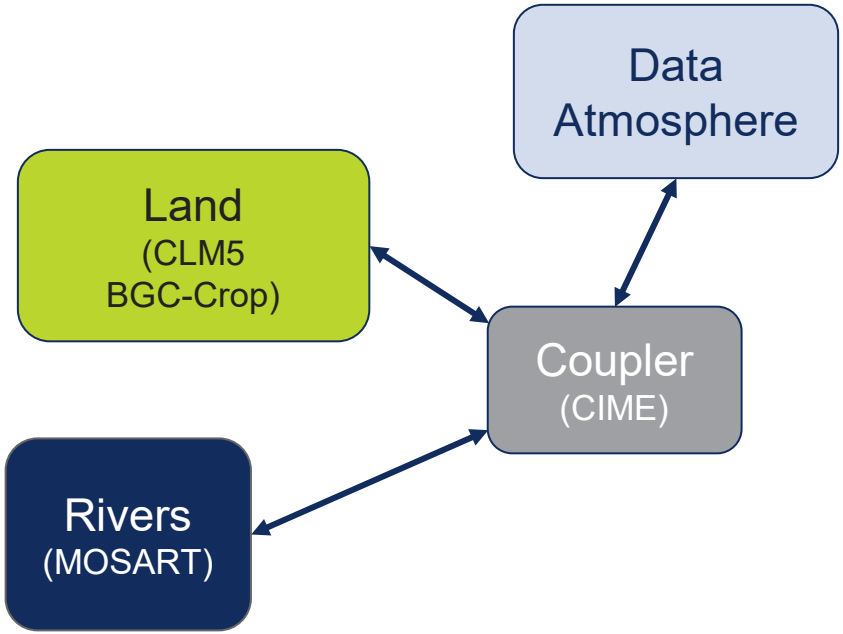
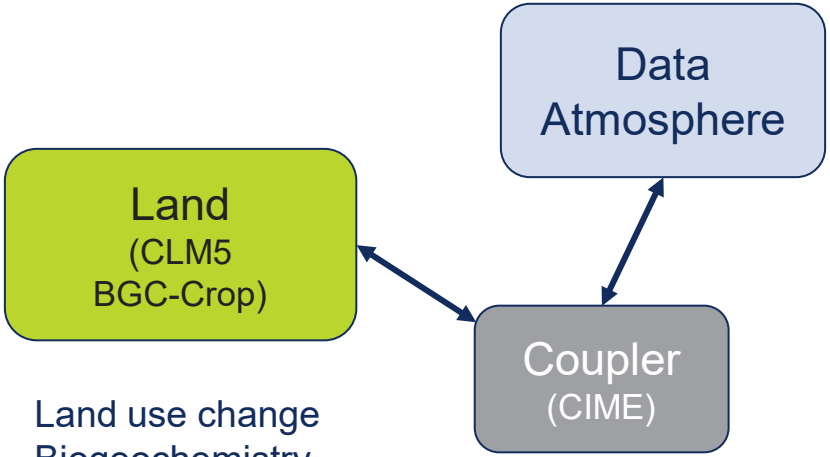


CESM supports a range of climate science research through a single model code base

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
- …

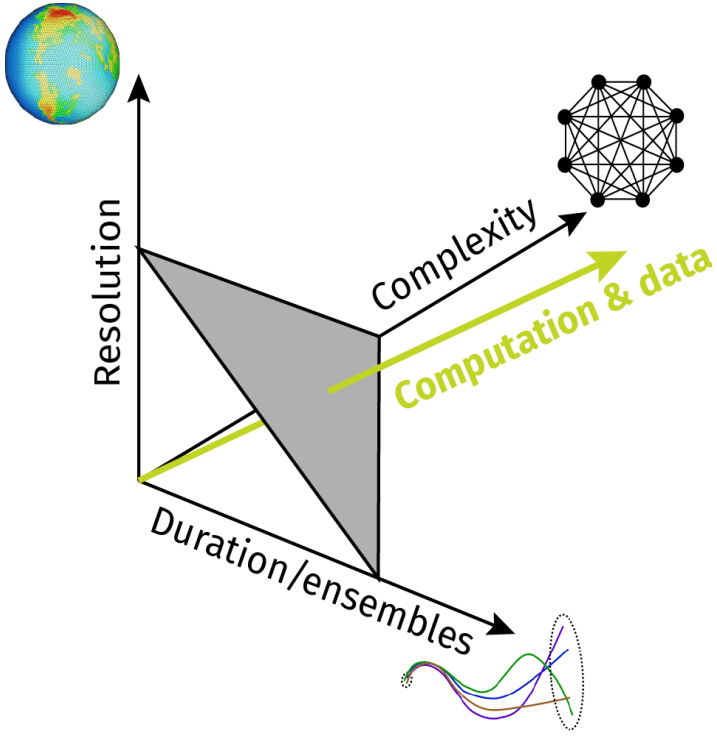
Earth System models and data can be a tool in your research toolbox

- **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 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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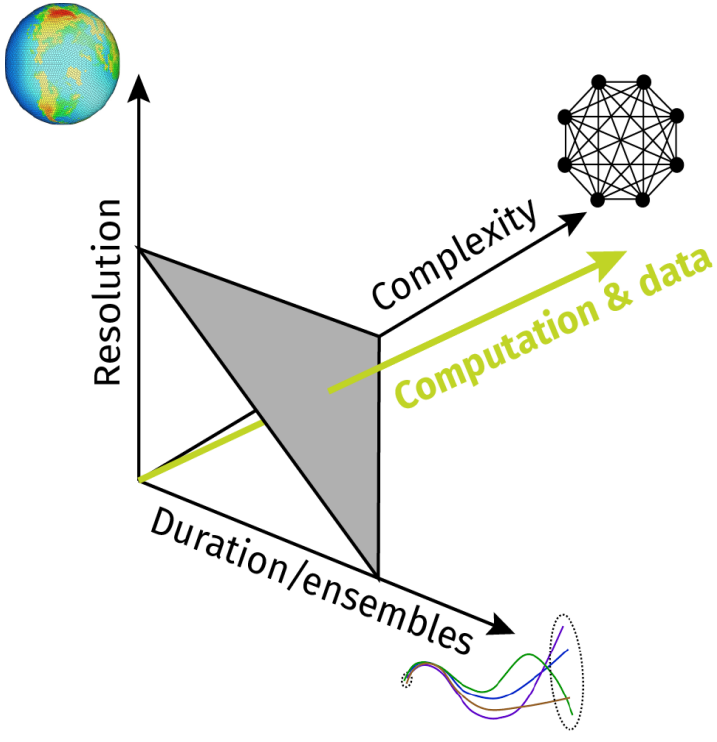
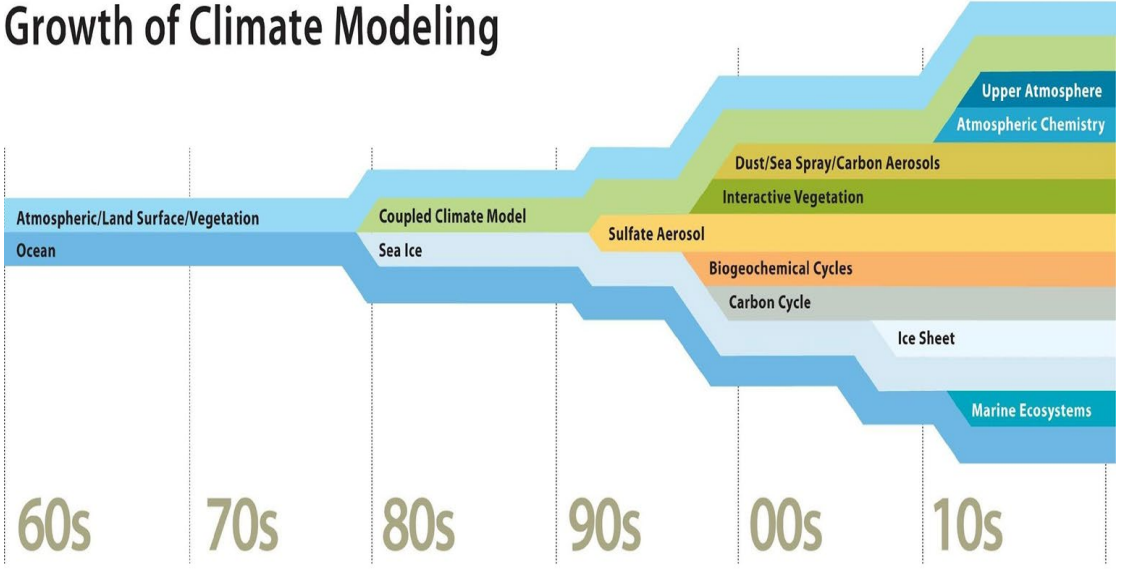


Complexity



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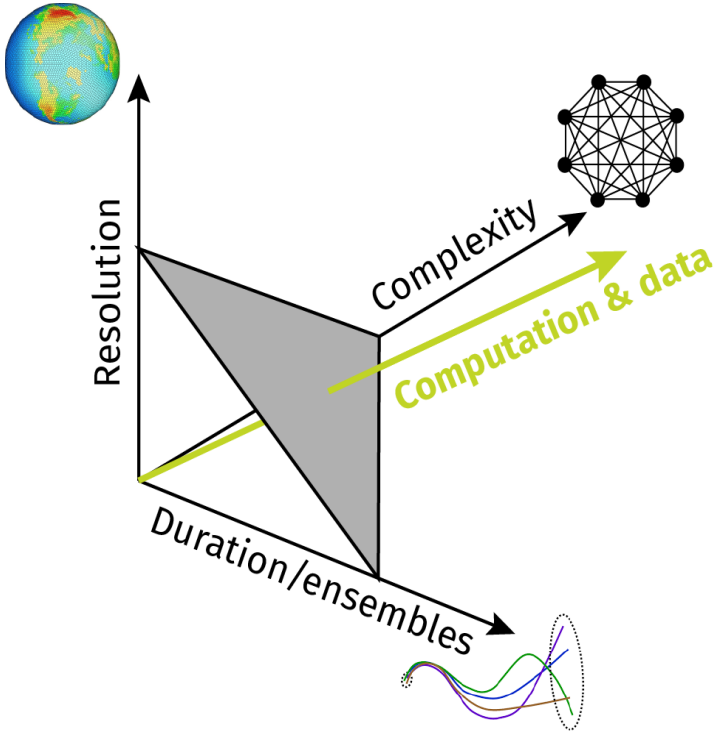
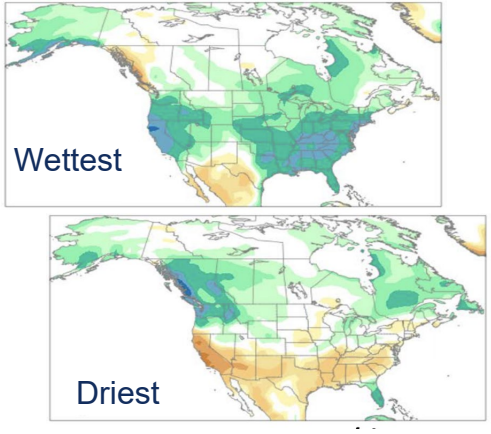
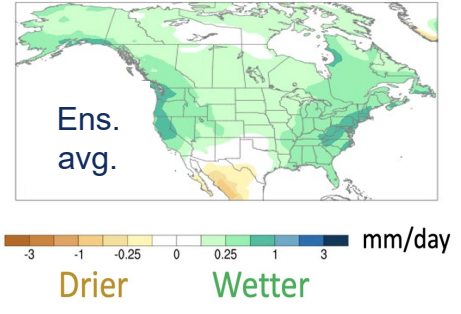


Large ensembles
climate change uncertainty

Internal vs Forced



Winter Precipitation Trend
(2010-2060)



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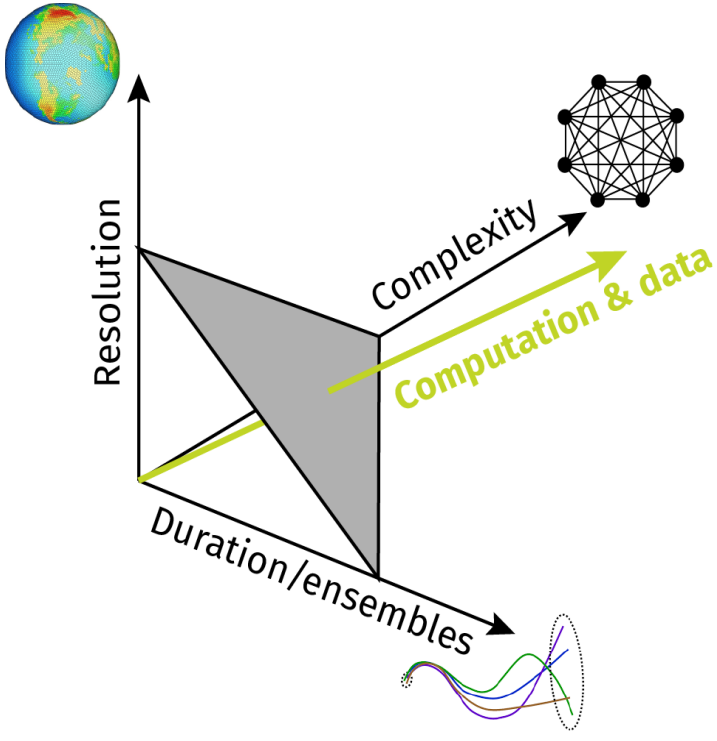
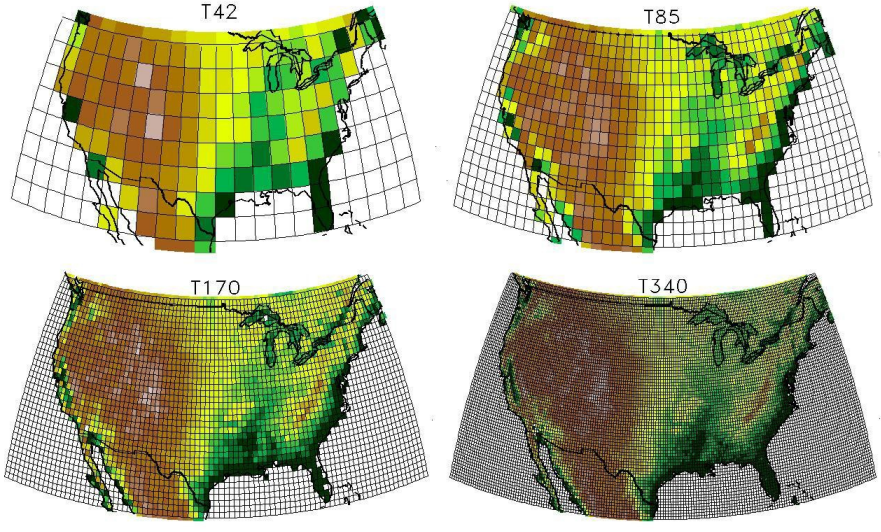


Resolution



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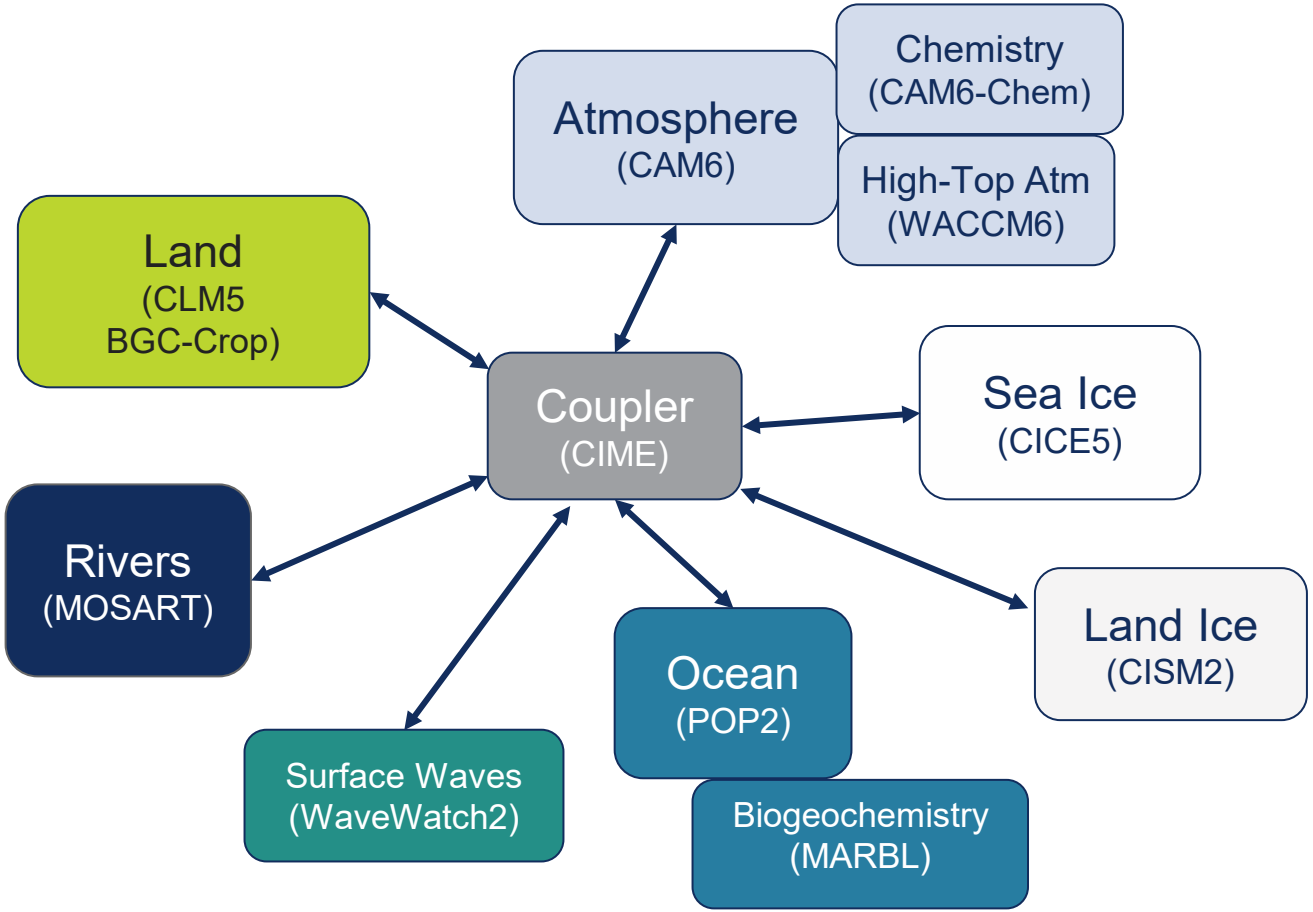
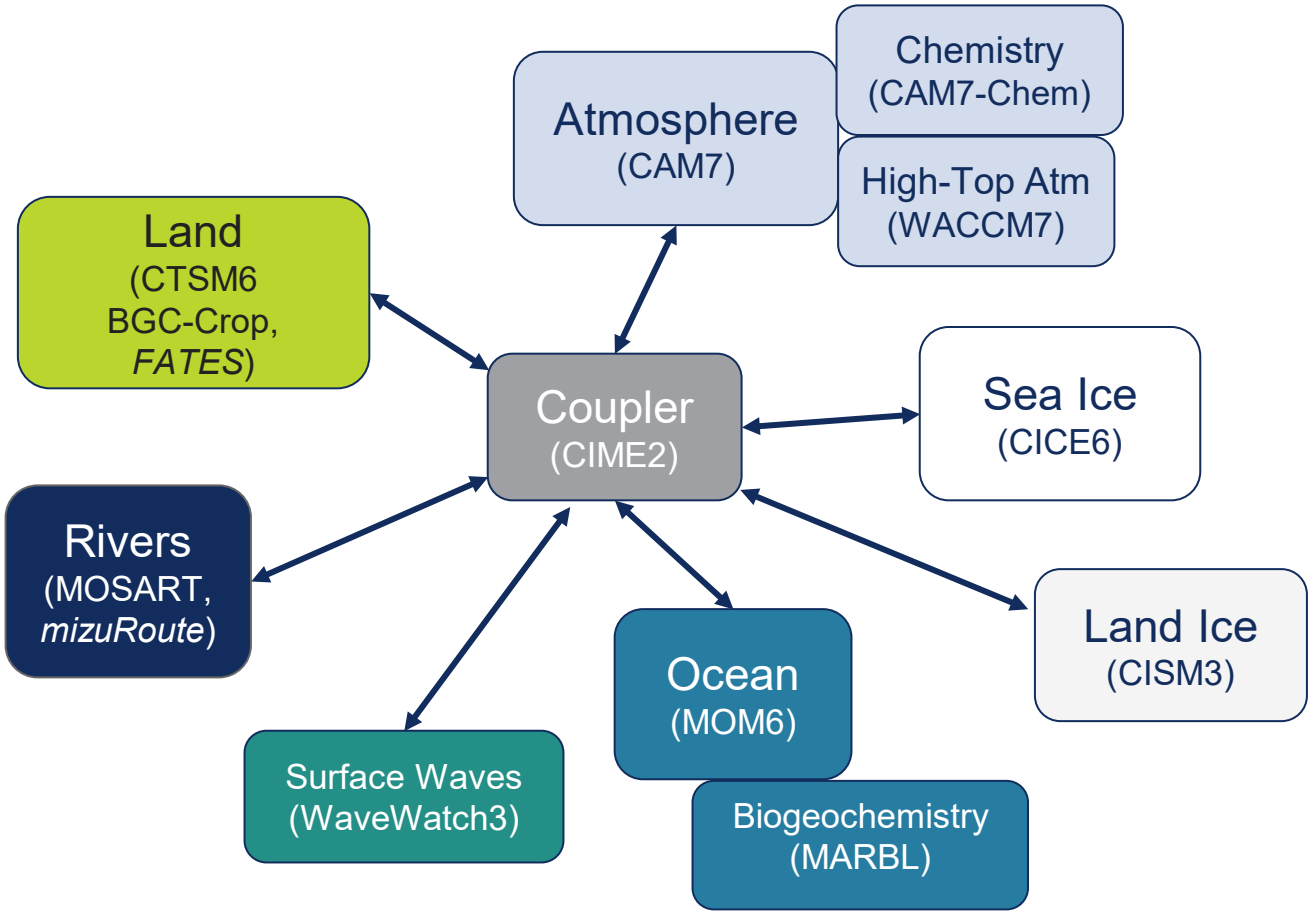


Working towards CESM3

Significant updates to all component models

Will use CESM3 for CMIP7

Trying to release CESM3 to the research community in summer 2025



Selected updates for CESM3

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

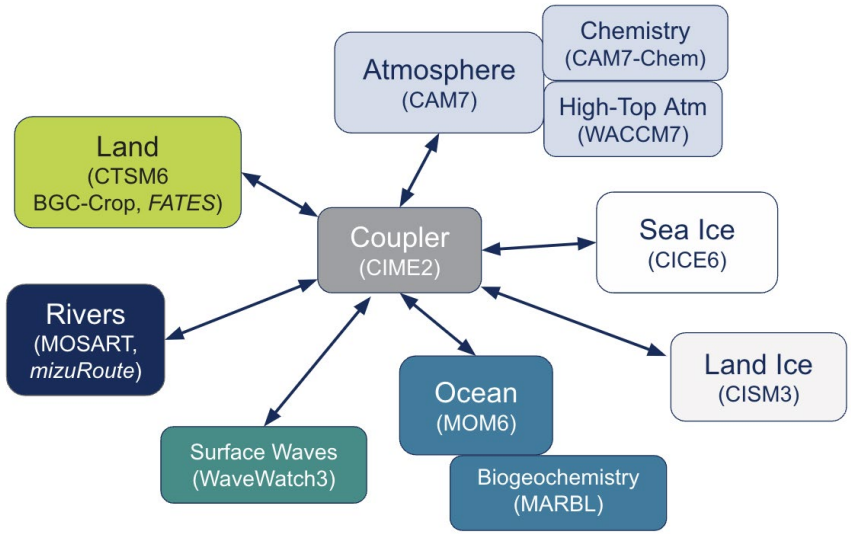
Ocean: MOM6, hybrid coordinate, variable sea level, tracer budgets within the Lab Sea, stochastic GME, isopycnal diffusion (Redi), …

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

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

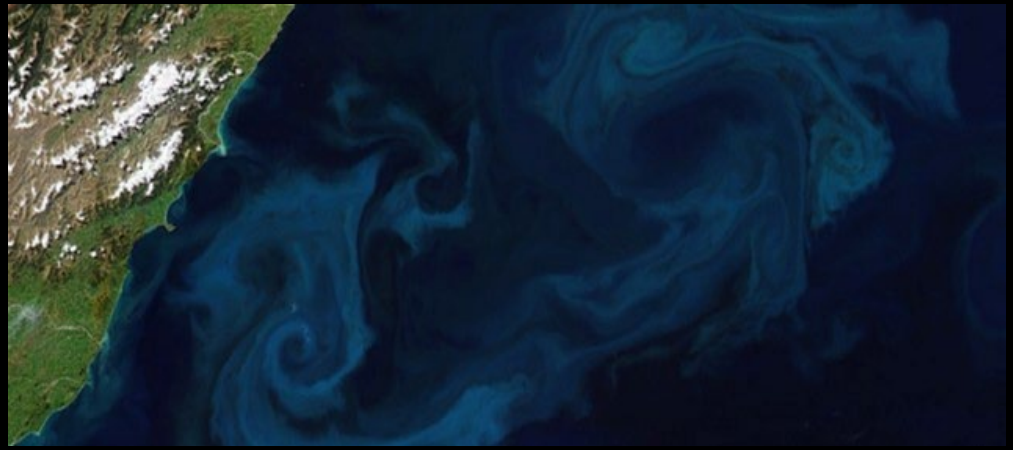
Will we have enough water?

Image: Kimon Maritz

Will we be able to grow or harvest enough food?

Can we produce it sustainably?

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



Forces driving the future of Earth System modeling

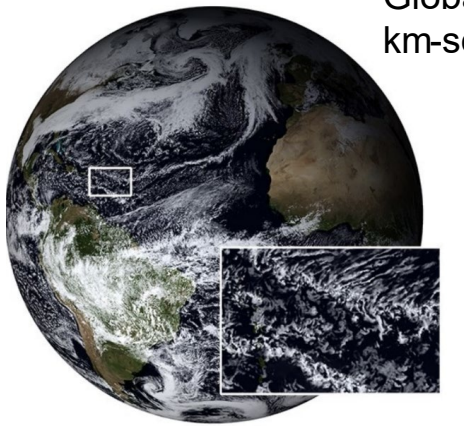
- Urgent need for actionable climate change information (climate risks, consequences of intervention/mitigation)
- *Earth System* prediction across timescales (ESPAT), S2S → S2D → 30-yr projections (ideally, seamless)
- Increasing demand for high -resolution (~0.25 °) and ultra high -resolution (km -scale) configurations in modeling hierarchy
- Growth and potential of machine learning, hybrid modeling, and emulators to transform models
- Changing computing architectures → need for code modernization
- Calls for improved accessibility of ESMs and output (e.g., to global south)

Image: Getty images

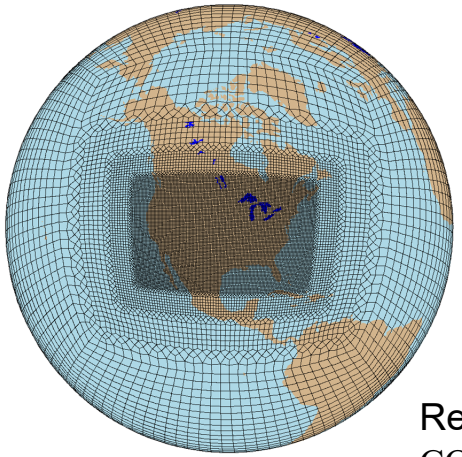
These drivers present many opportunities and challenges for the CESM activity

CESM high-resolution progress and plans

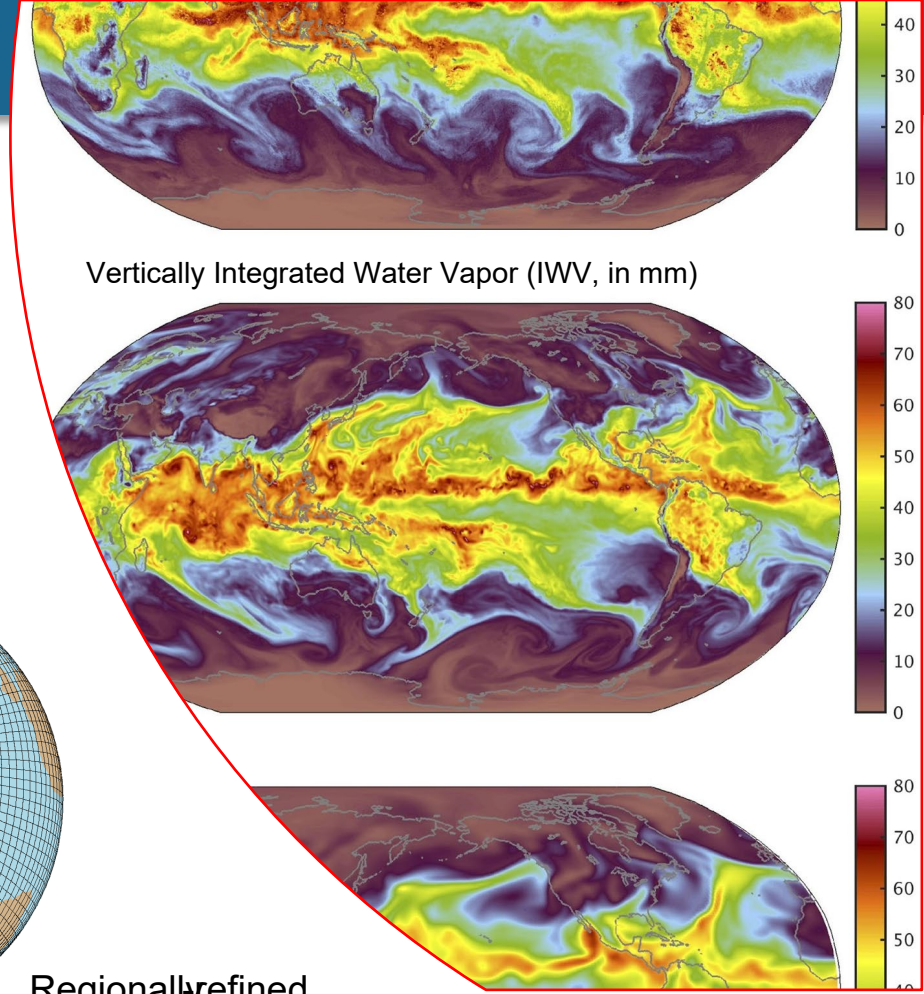
- CESM1.3(HR): 0.25° atm/lnd, 0.1 ° ocn
- Developing CESM3 HR version
- CESM EarthWorks and STORMspeed projects developing km -scale configuration
- Several regionally -refined grids available



Global
km-scale



Regionally-refined
CONUS, ⅛ deg



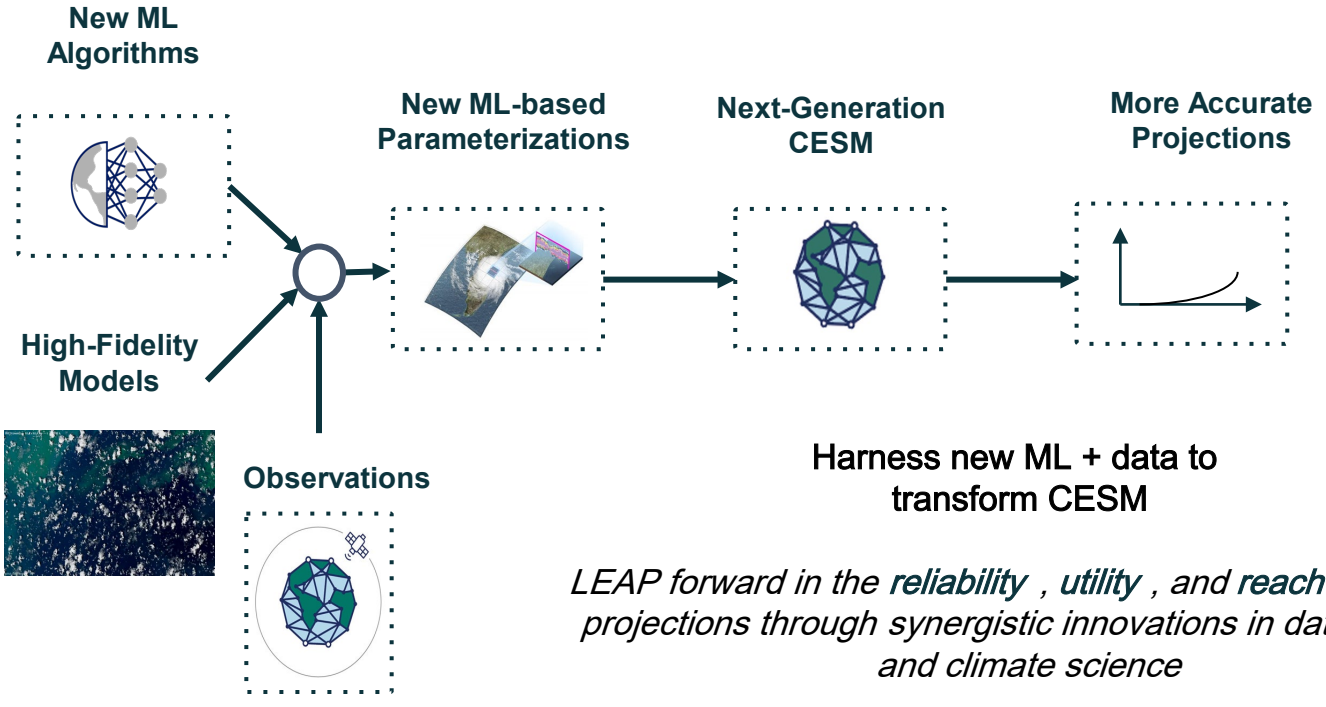
Chang et al. (2020, JAMES)

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



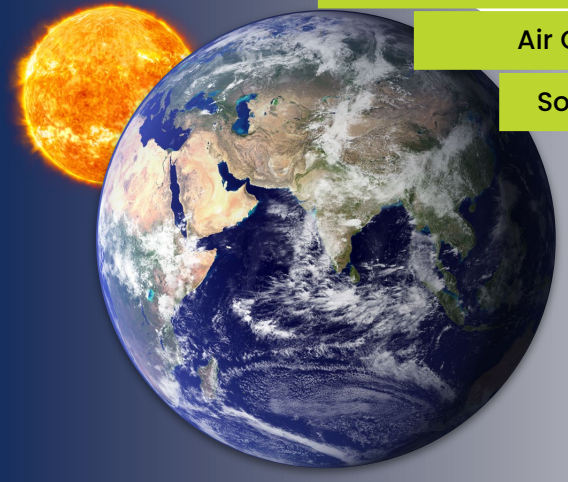
Harness new ML + data to transform CESM

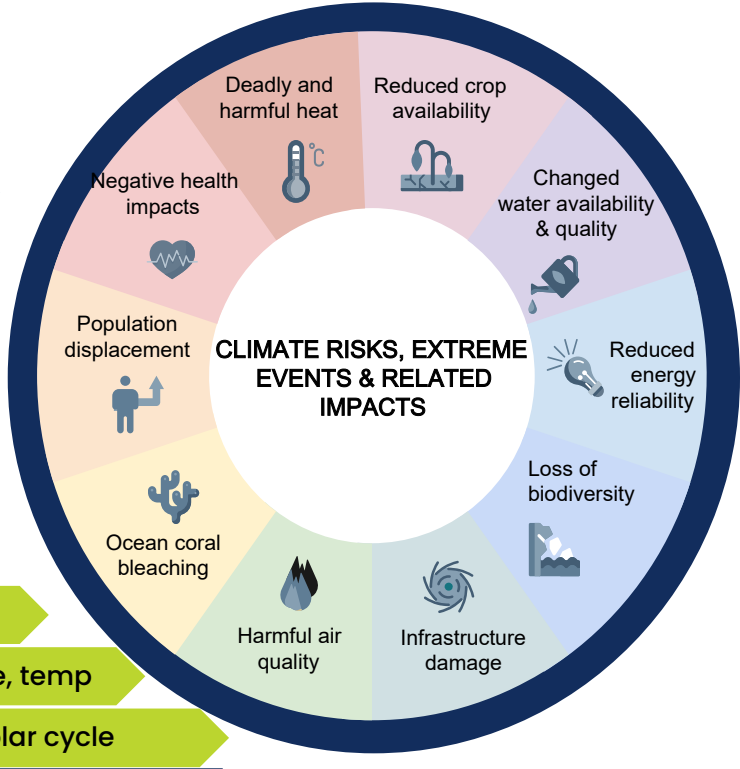
*LEAP forward in the **reliability** , **utility** , and **reach** of climate projections through synergistic innovations in data science and climate science*

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

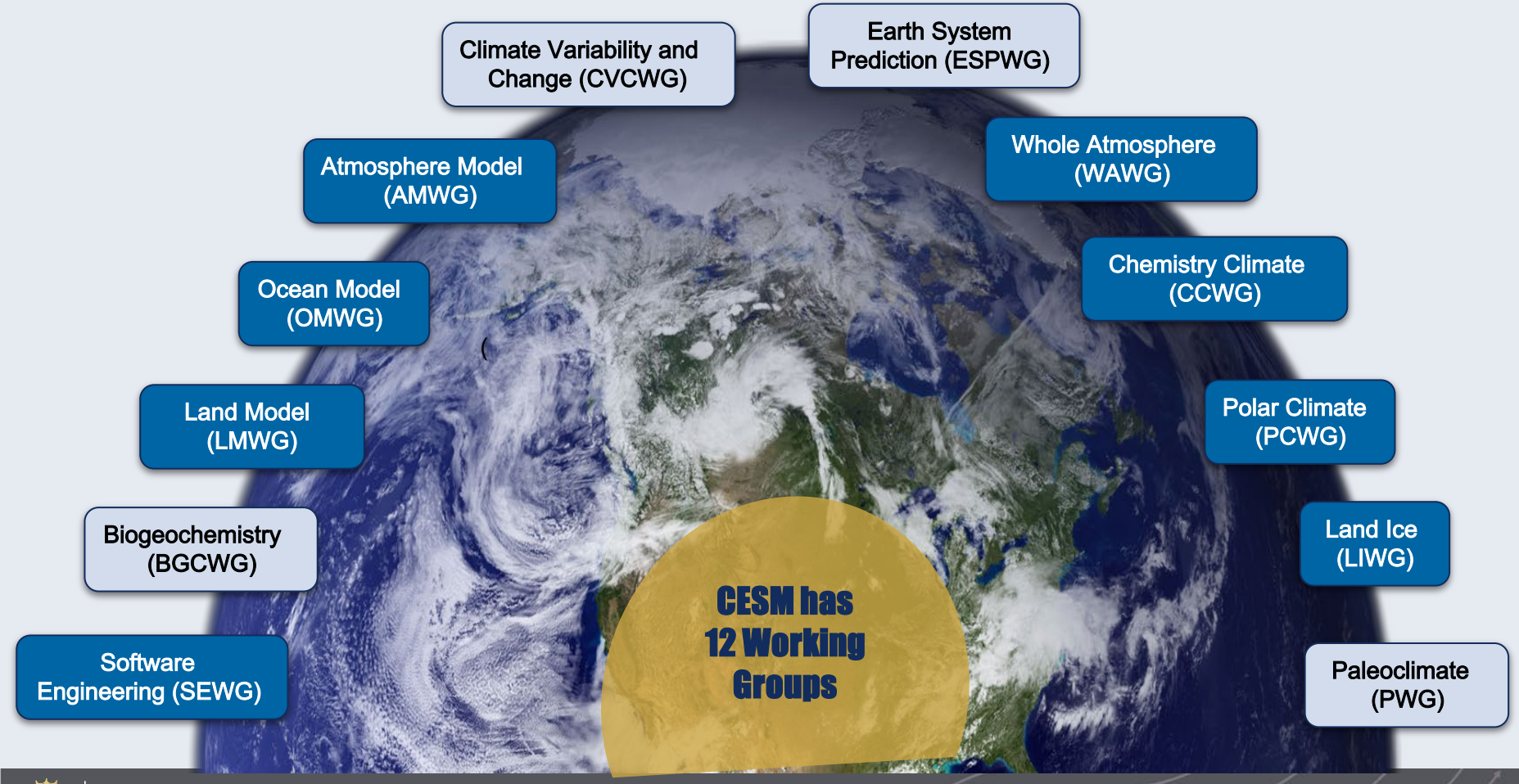




Minutes → Centuries

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

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



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)

Welcome to the CESM community!

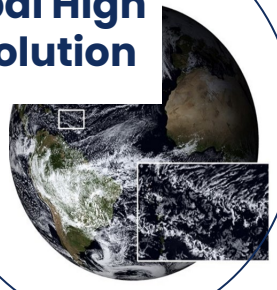
Unified modeling framework

“Pick and Choose” menu of options

–

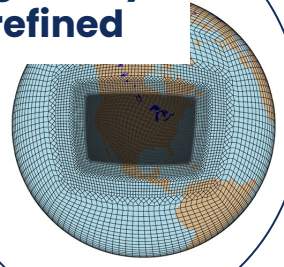
All components interact and are ready to play

Global High Resolution

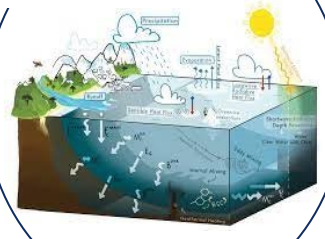


Global Low Resolution

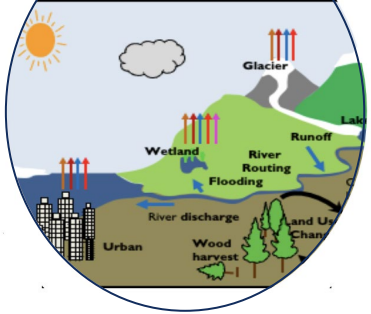
Regionally-refined



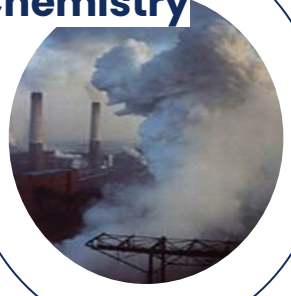
Ocean



Land / Hydrology



Chemistry



Space Weather