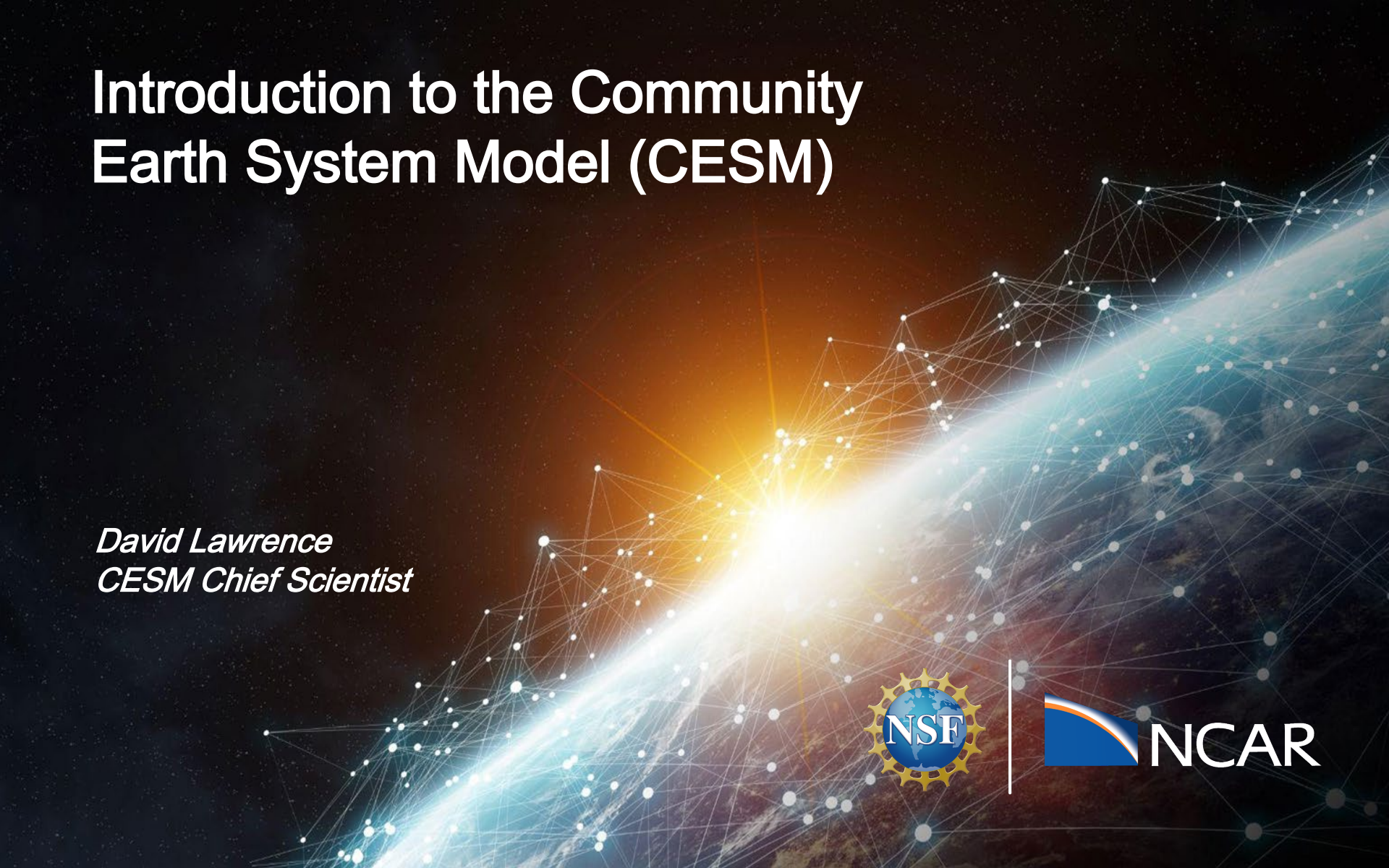
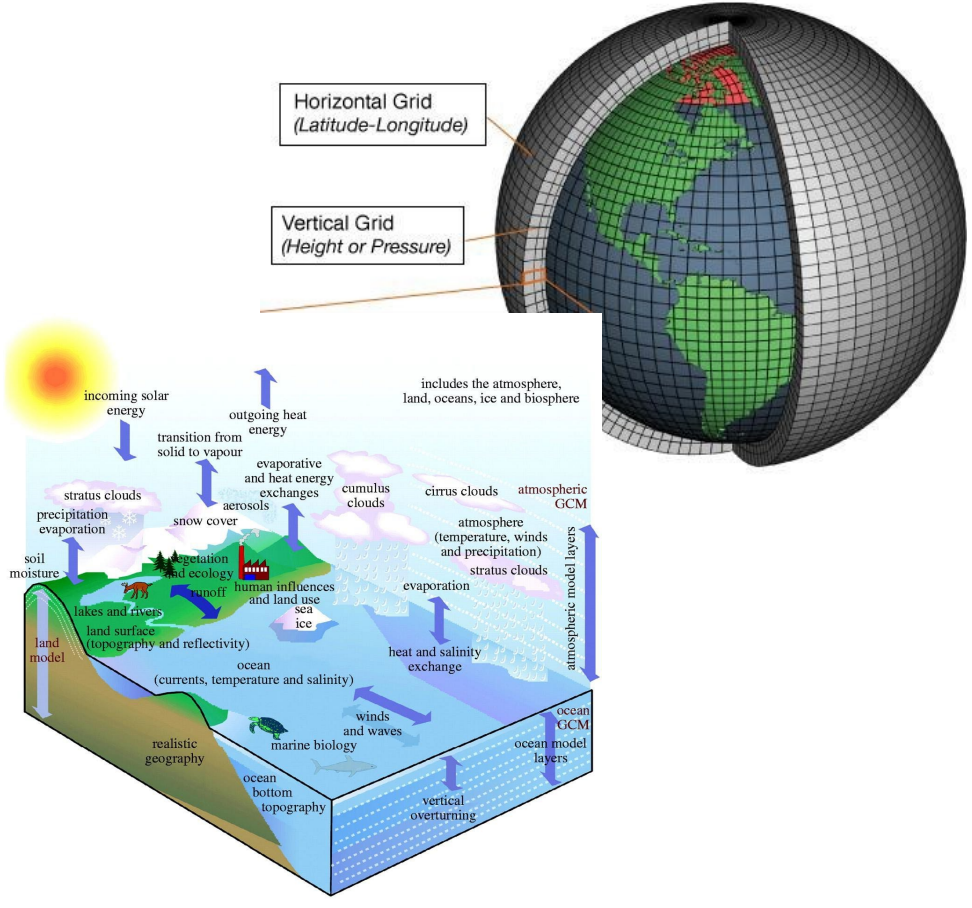
Introduction to the Community Earth System Model (CESM)

David Lawrence
CESM Chief Scientist

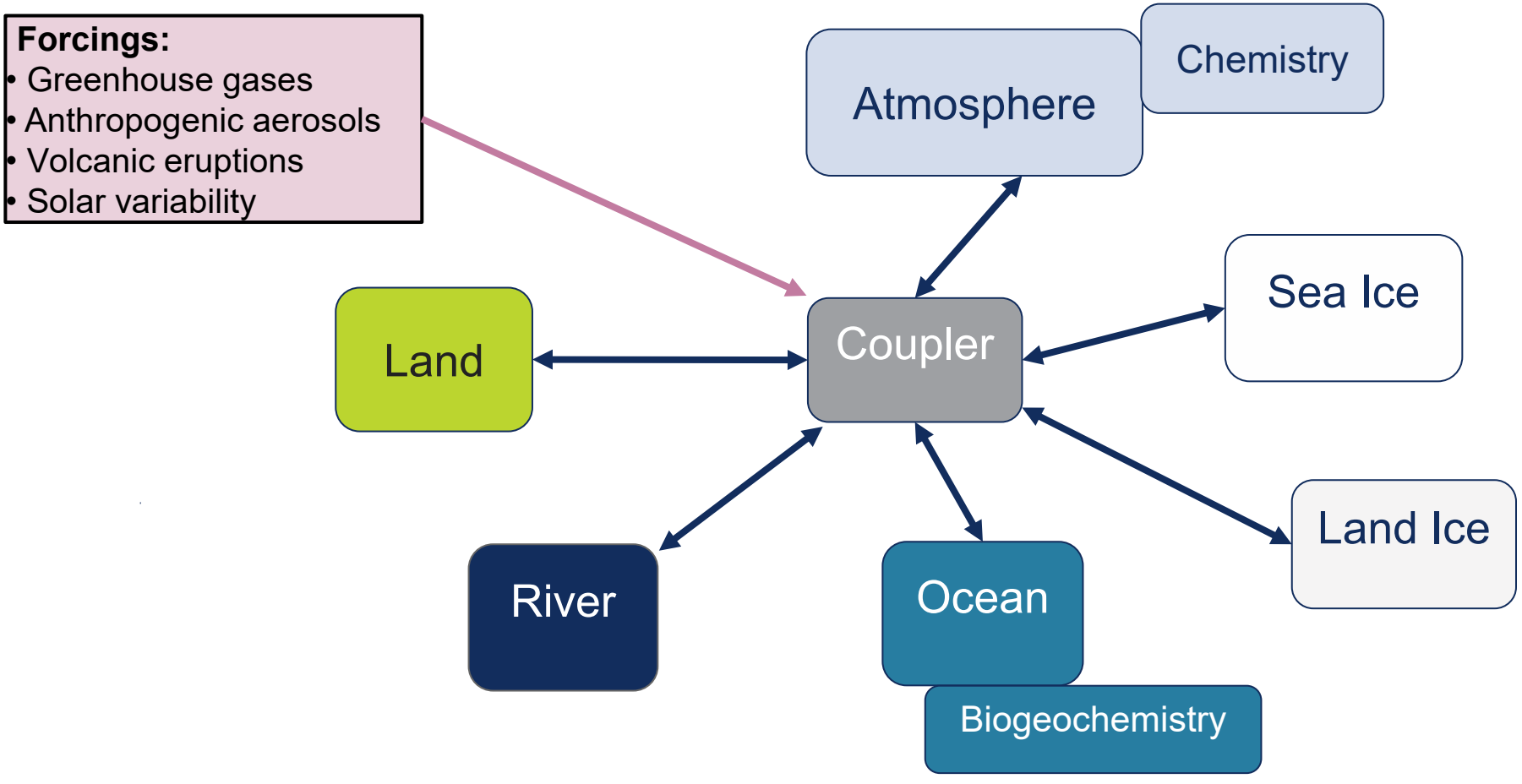


Global Earth System Models

- 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)



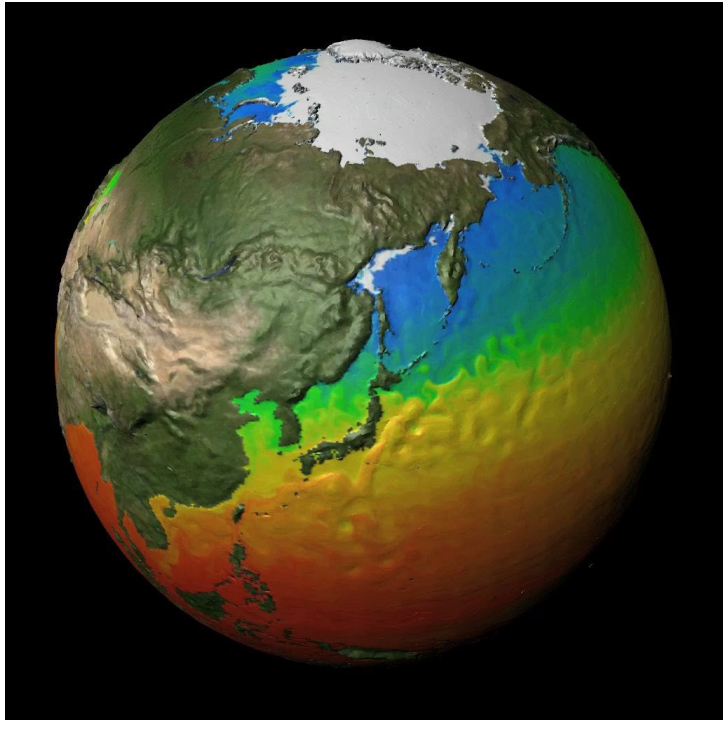
Structure of a fully coupled Earth System Model



Global Earth System Models

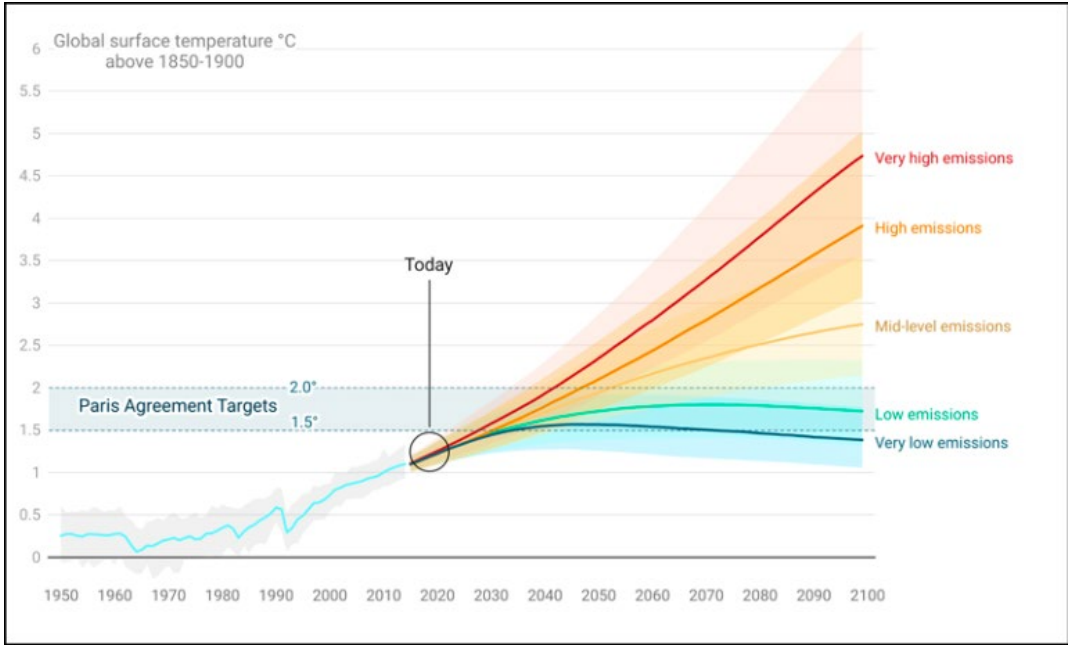
Many purposes including:

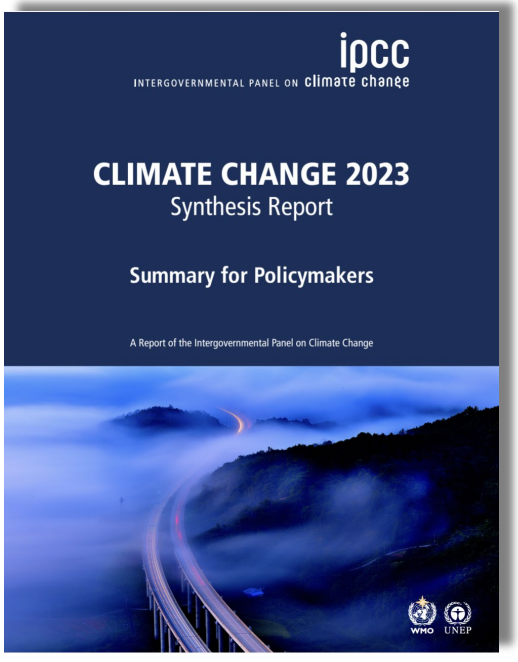
- Scientific and mechanistic understanding of past observed events and changes
- Studying recent past, present, and future (projections) climate changes and their impacts
- Understanding climate variability
- Subseasonal-to-multidecadal Earth system predictions
- Providing actionable, societally-relevant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



Small and Scheitlin

Output from Earth System Models is key basis for IPCC reports





IPCC, AR6 Report

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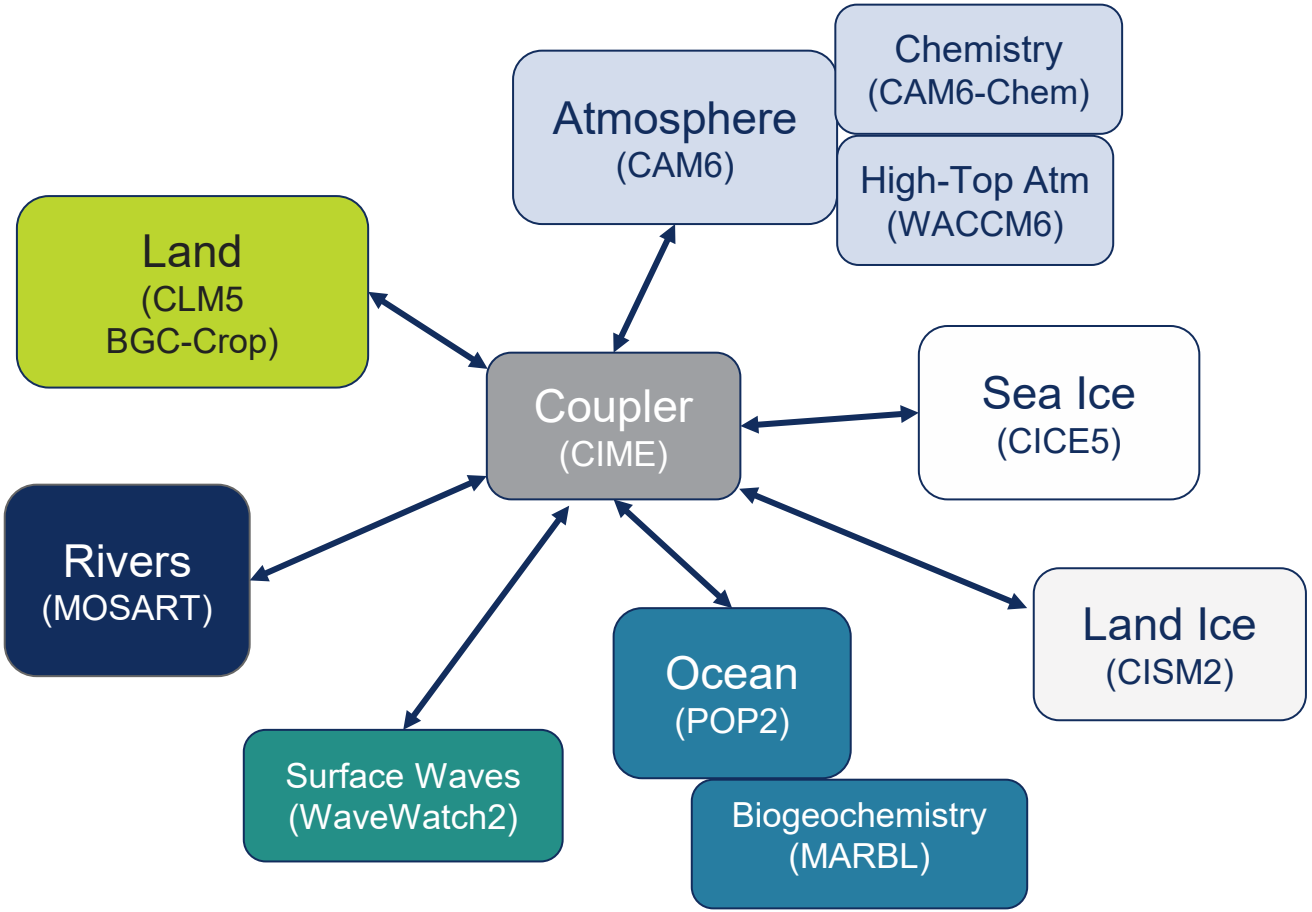
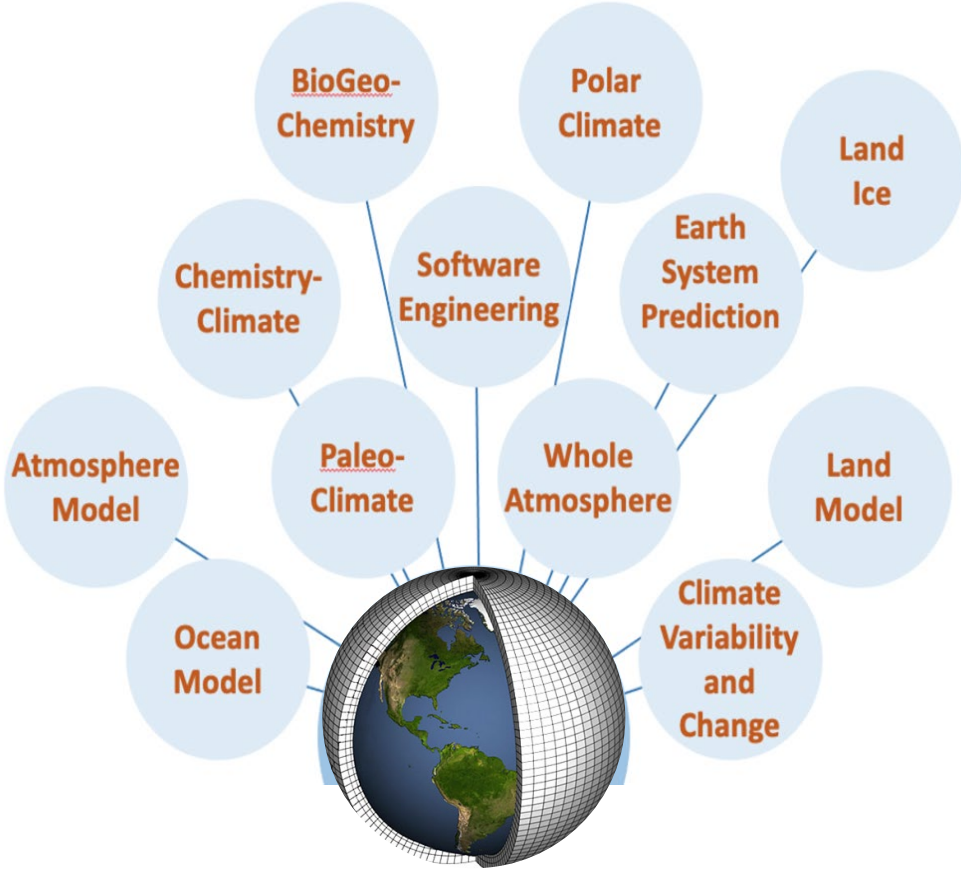
Model configuration used for simulations submitted to the Coupled Model Intercomparison Project (CMIP6) and many other community simulations (e.g., CESM2 Large Ensemble)



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

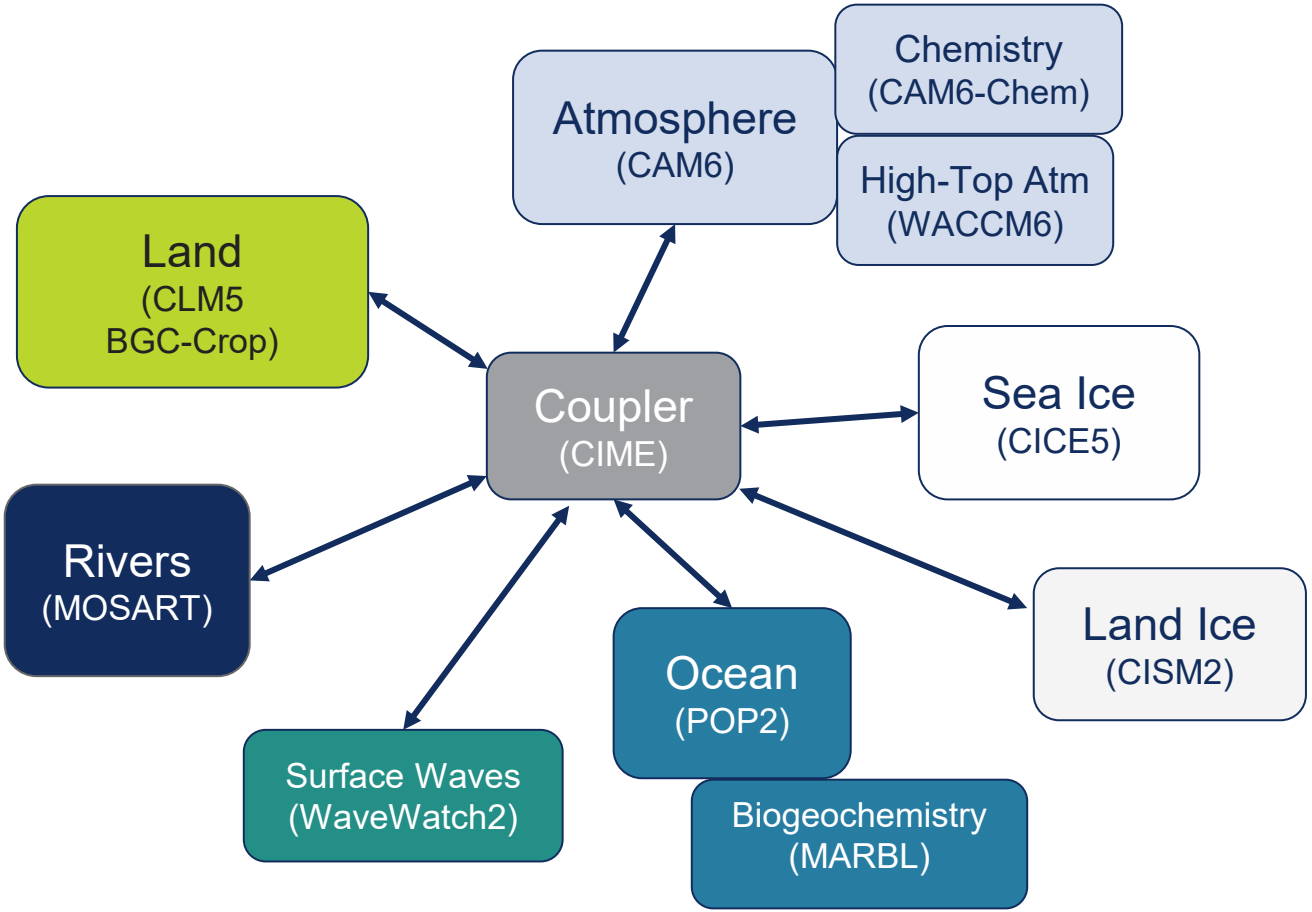


CESM is a virtual laboratory for the research community

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
- ...

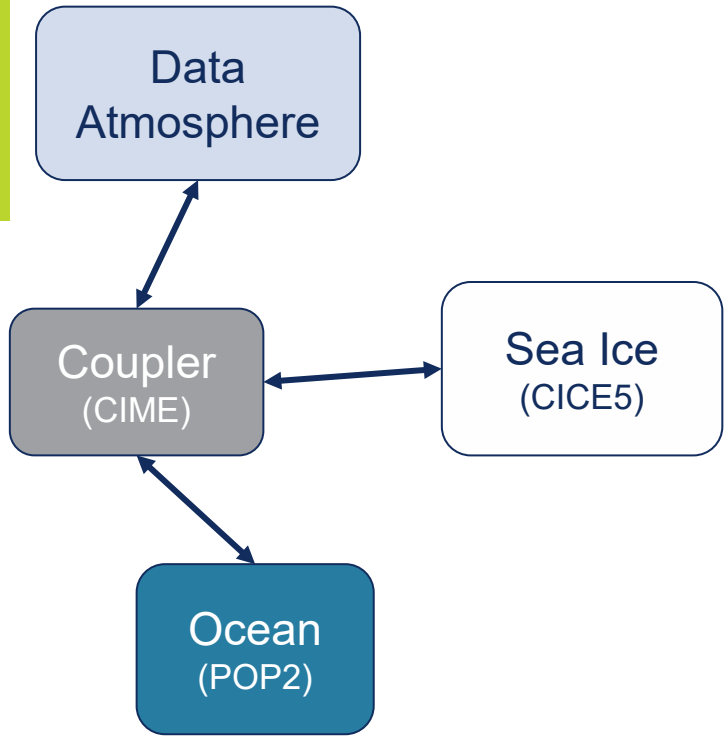
CESM supports a range of climate science research through a single model code base



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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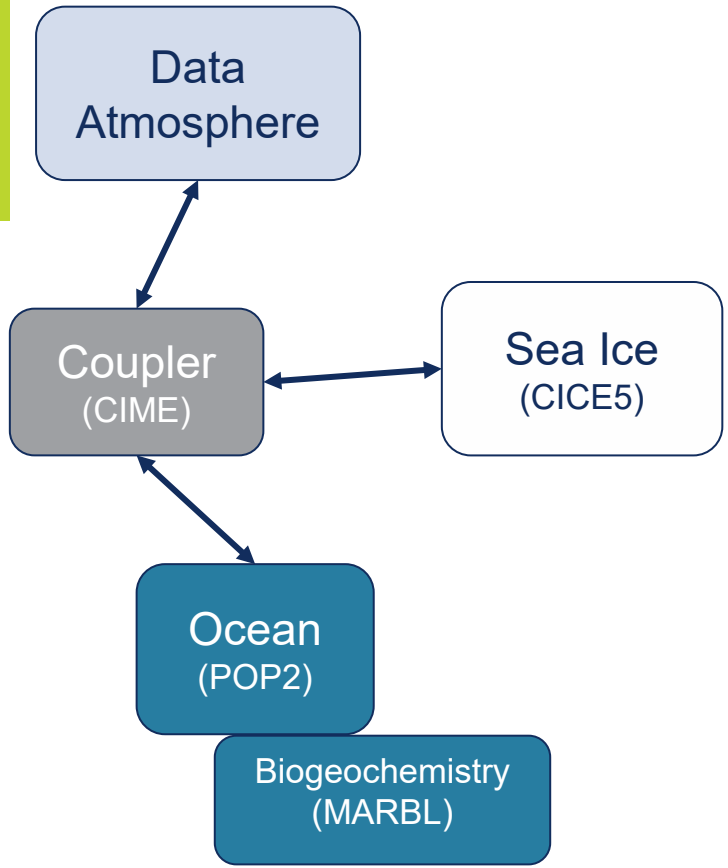

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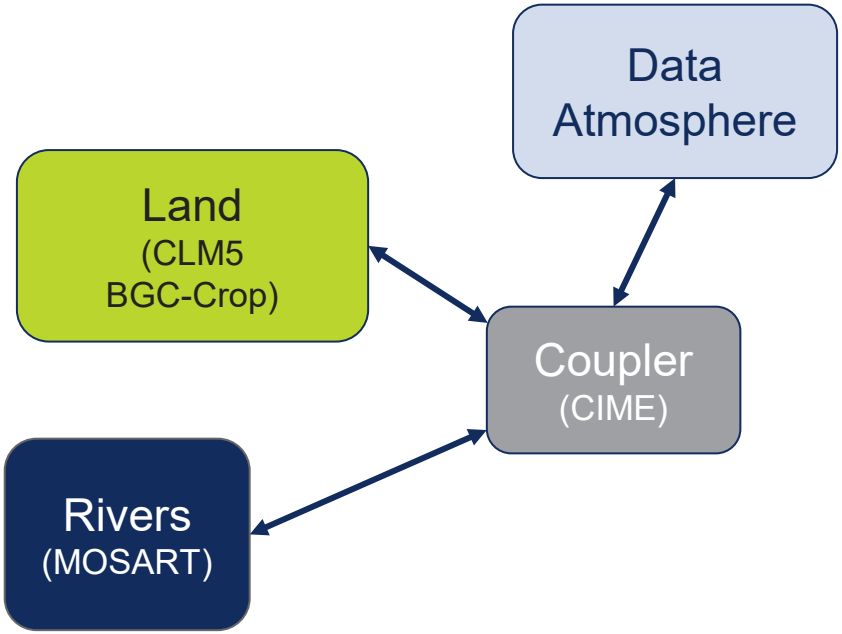
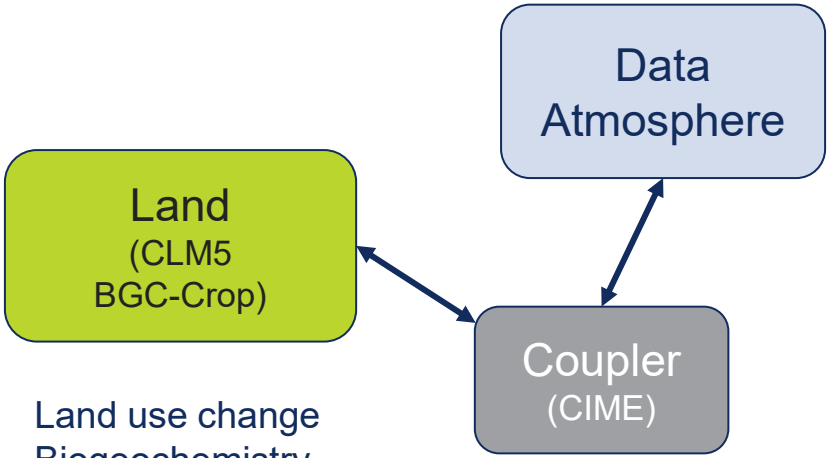


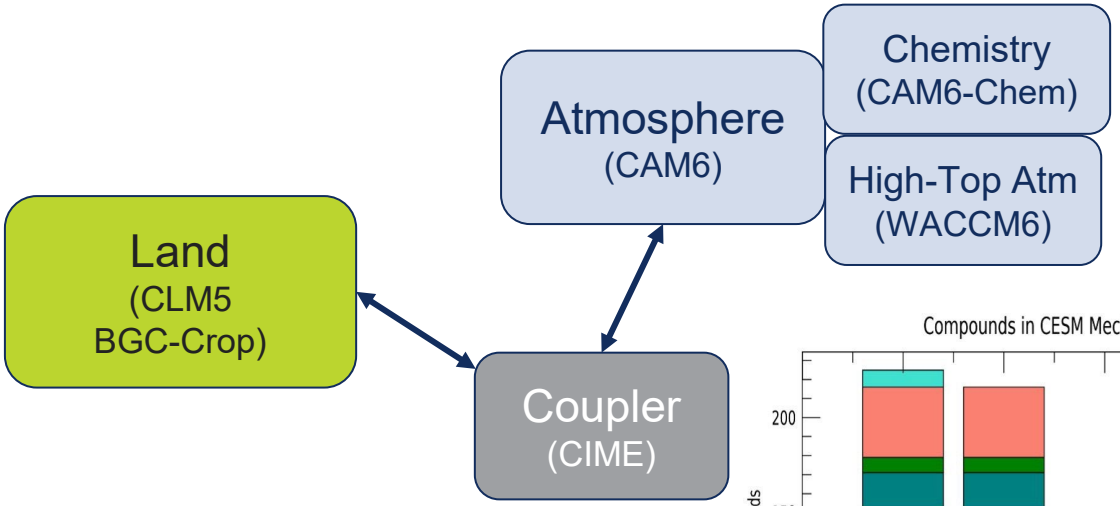
CESM supports a range of climate science research through a single model code base

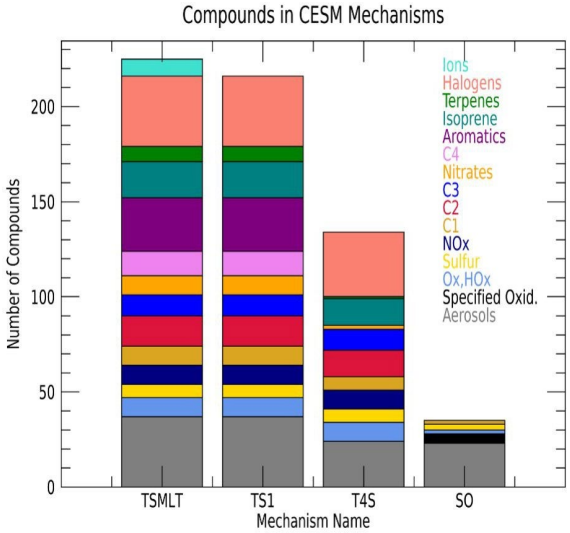
And, within each component model, there are many choices you can make about parameterizations, complexity levels, etc.



- 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





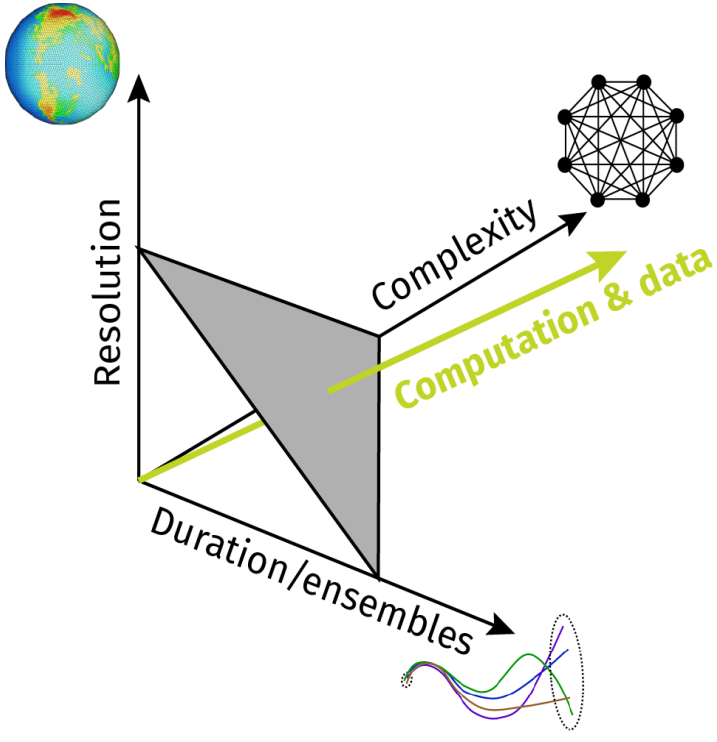
Earth System models and data can be a tool in your research toolbox

- **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 science questions

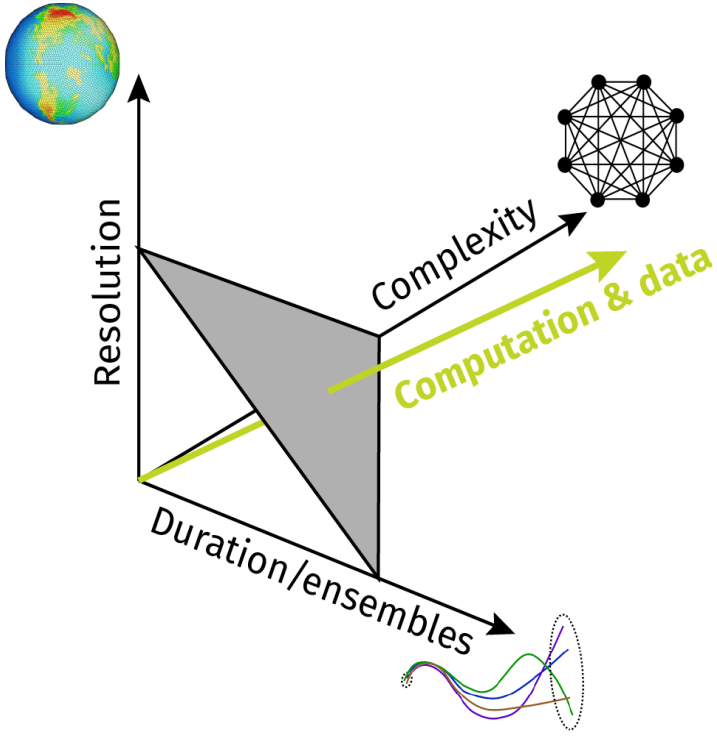
- **But, that's just the beginning …**
  - learning how to usefully apply ESMs and ESM data to answer research questions never ends
  - advice: be creative, acknowledge that there will be missteps, have fun!

Earth System Modelling is hard!

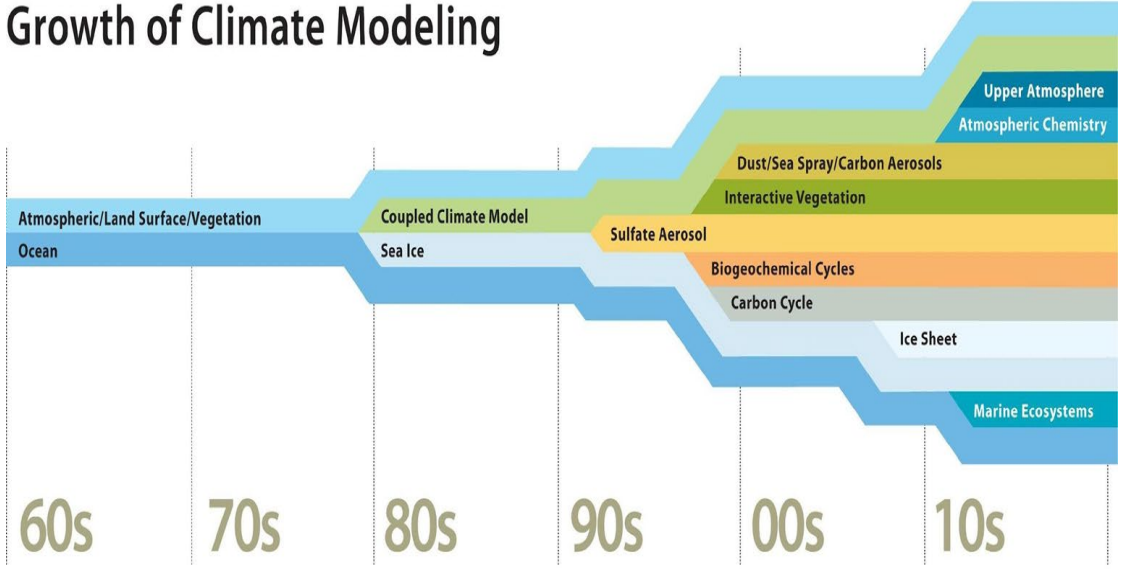
Different research questions require different considerations



Different research questions require different considerations



Complexity



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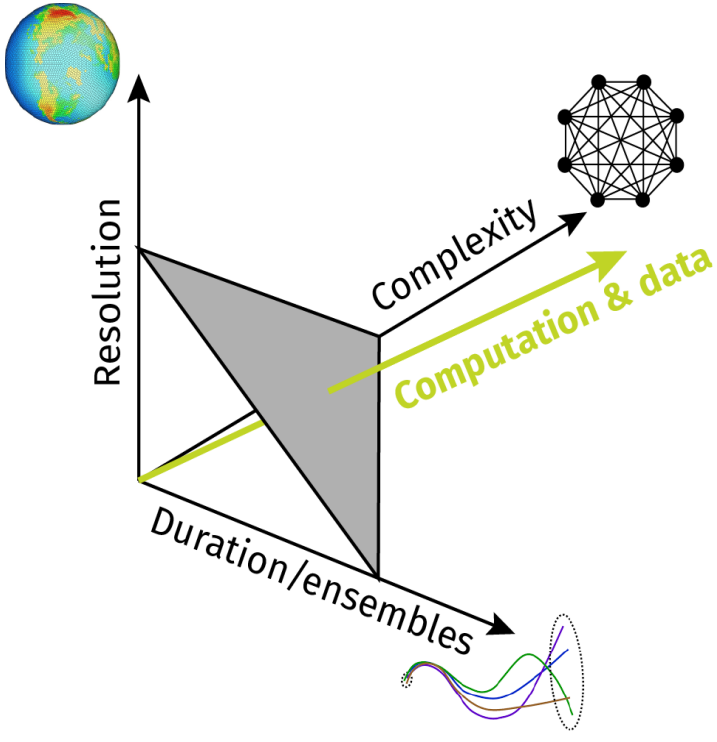
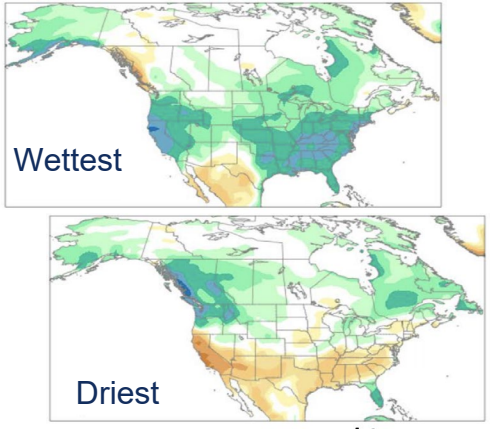
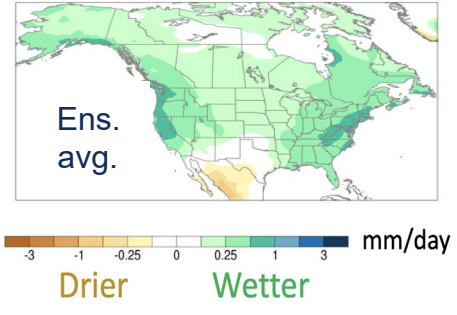


Large ensembles
climate change uncertainty

Internal vs Forced



Winter Precipitation Trend
(2010-2060)



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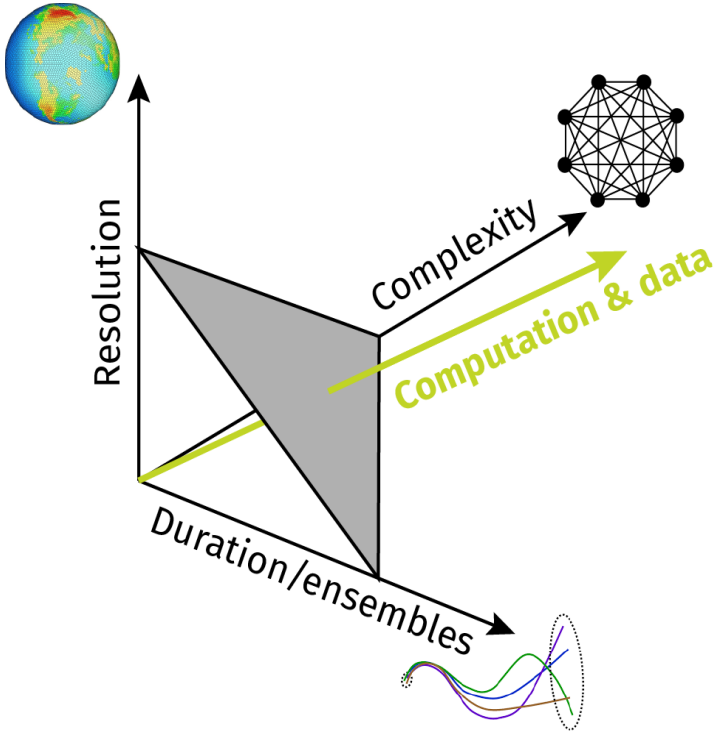
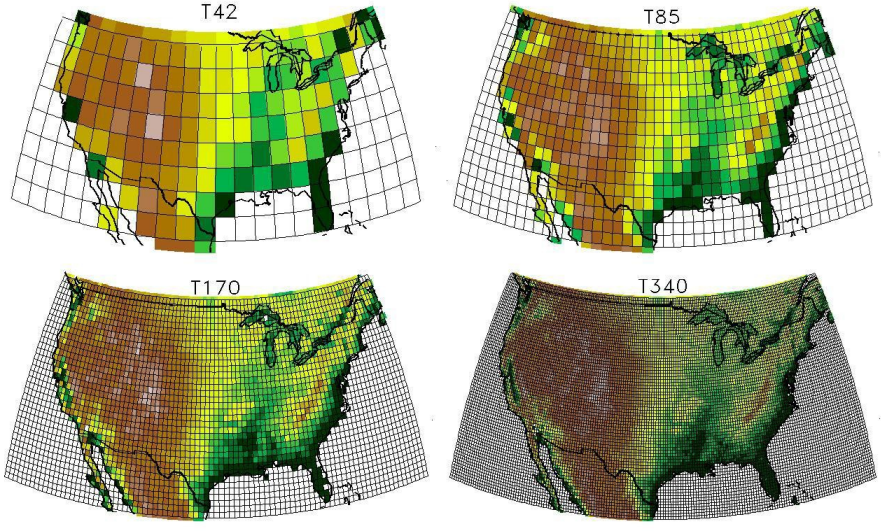


Resolution



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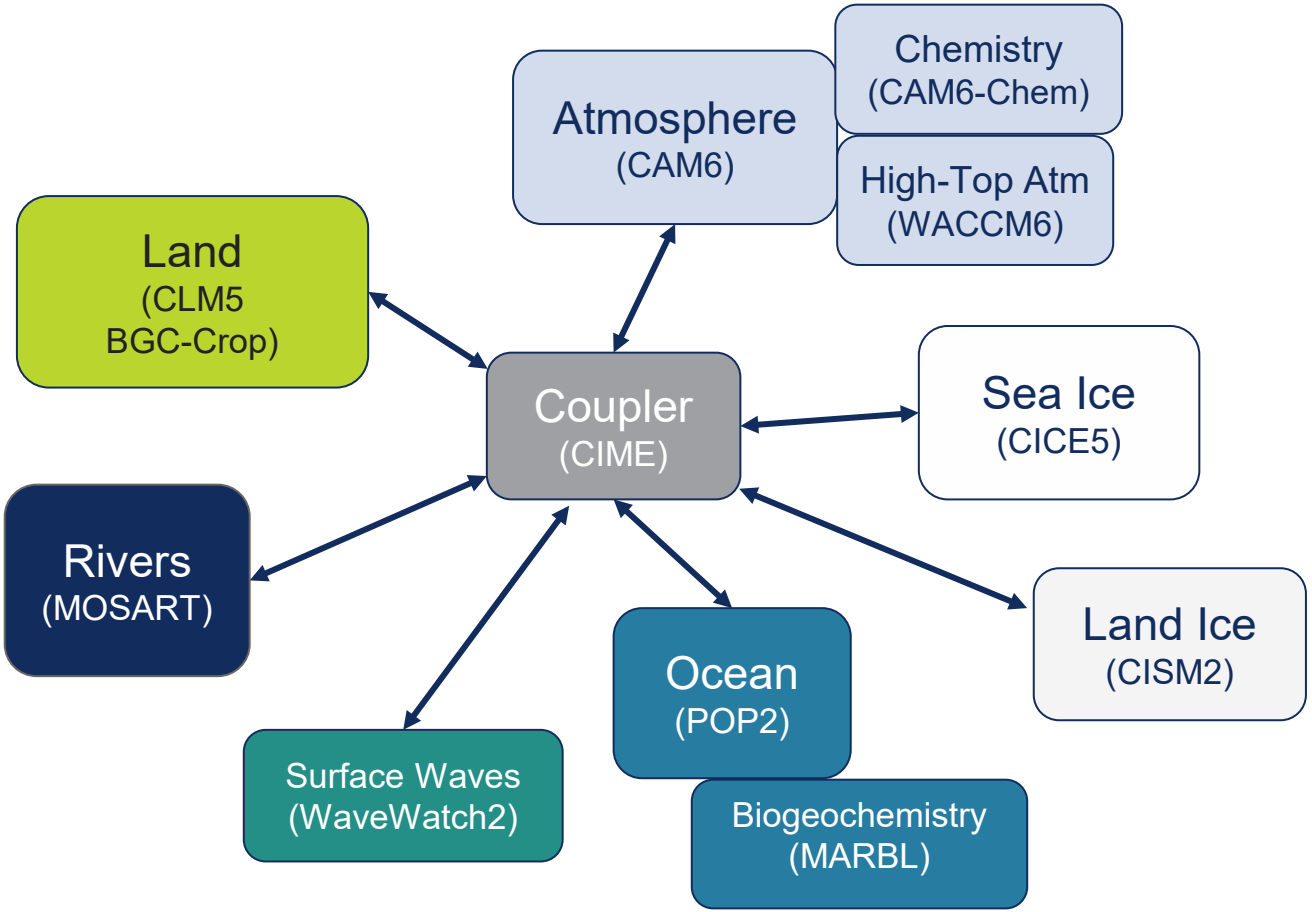
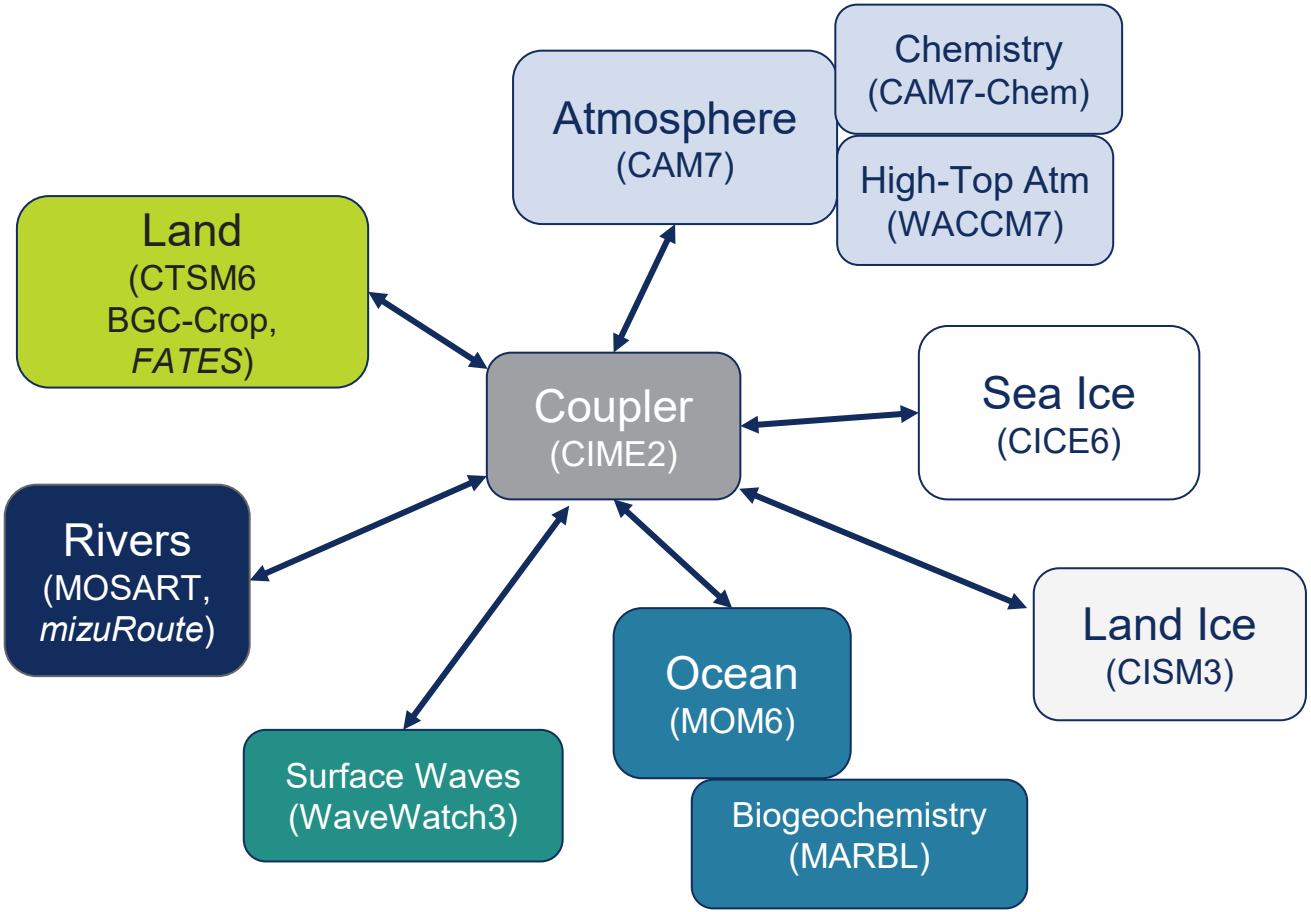


Working towards CESM3

Significant updates to all component models

Will use CESM3 for CMIP7

Trying to release CESM3 to the research community in early 2026



Selected updates for CESM3

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

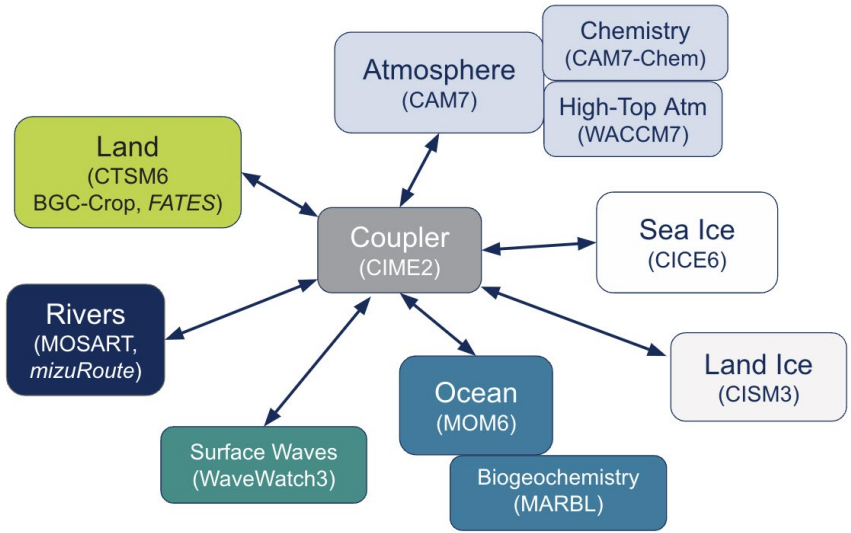
Ocean: MOM6, hybrid coordinate, variable sea level, tracer budgets within the Lab Sea, stochastic GME, isopycnal diffusion (Redi), …

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)

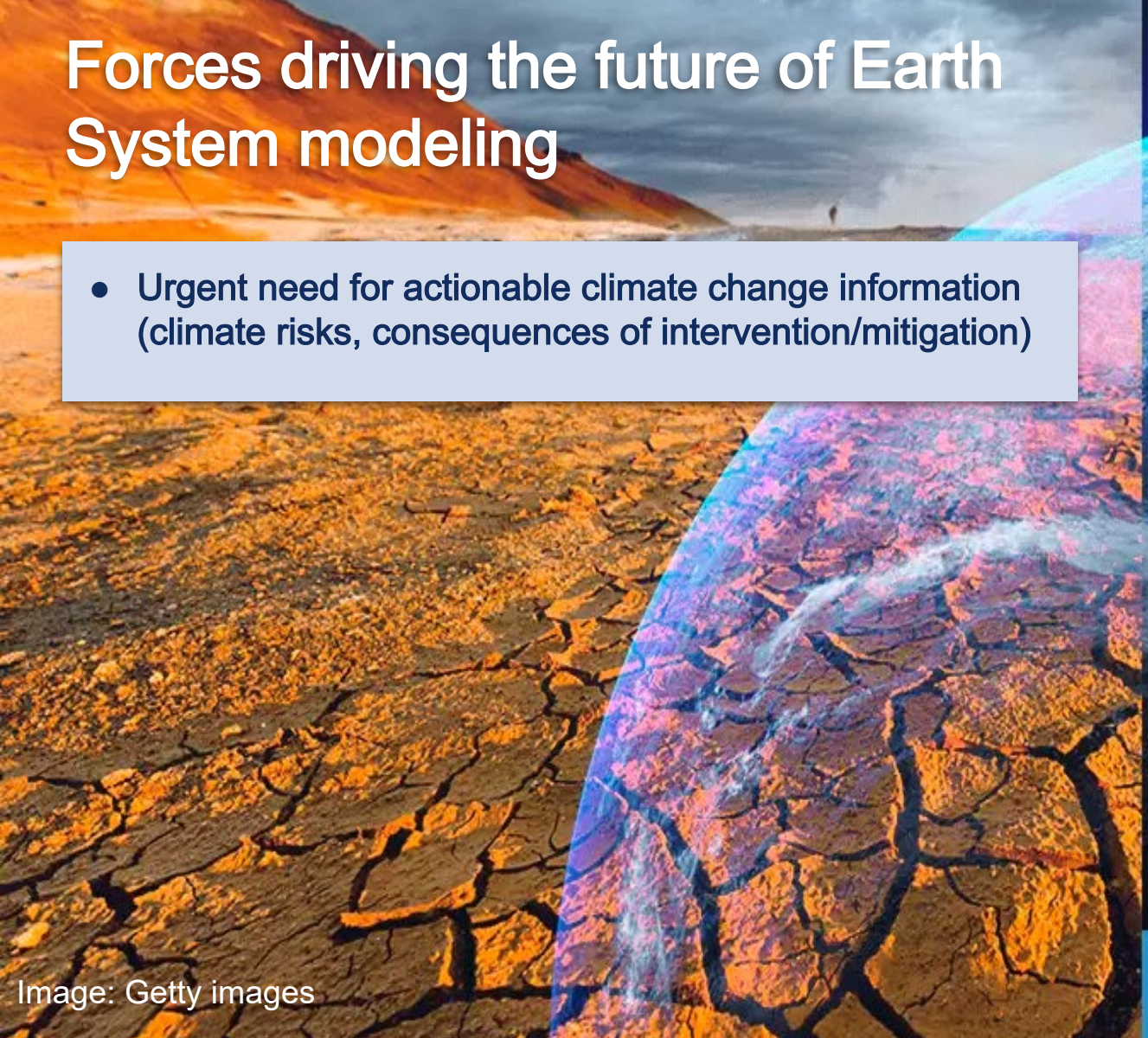


Image: Getty images

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

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Current Issue | First release papers | Archive | About

HOME > SCIENCE ADVANCES > VOL. 11, NO. 11 > CONFRONTING EARTH SYSTEM MODEL TRENDS WITH OBSERVATIONS

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

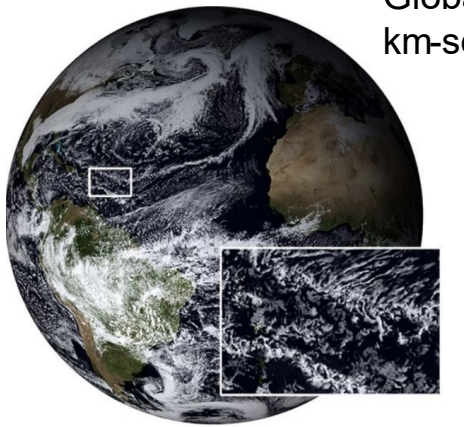
- Actionable information (climate risks, consequences of intervention/mitigation, tipping points)
- High-resolution (0.25°) and ultra high-resolution (km-scale) modeling configurations
- Machine learning, hybrid modeling, emulators
- Seamless Earth System Prediction and Predictability research across 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

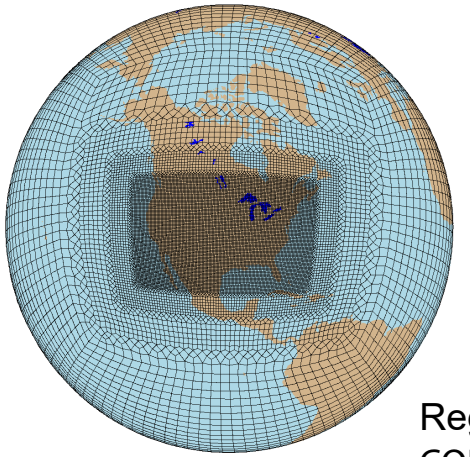
These drivers present many opportunities and challenges for the CESM activity

CESM high-resolution progress and plans

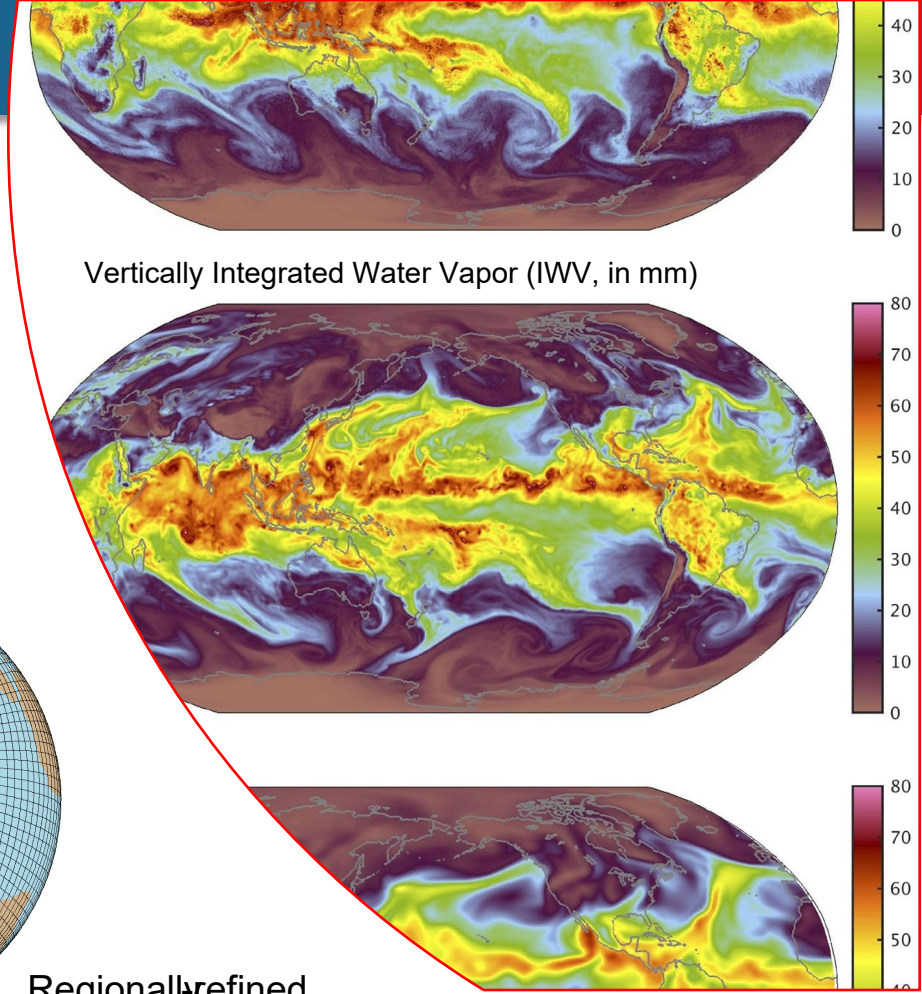
- CESM1.3(HR): 0.25° atm/lnd, 0.1° ocn
- Developing CESM3 HR version
- CESM EarthWorks and STORMspeed projects developing km-scale configuration
- Several regionally-refined grids available



Global km-scale



Regionally-refined CONUS, ⅛deg

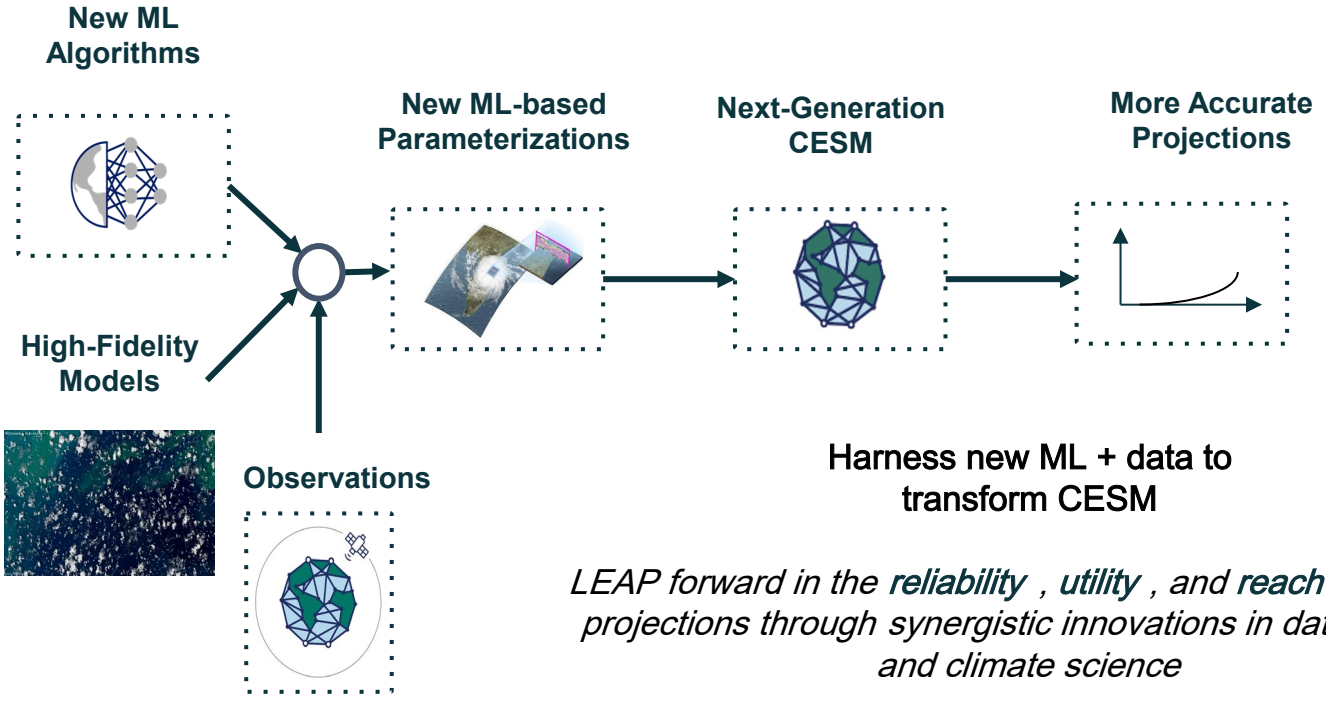


Towards a hybrid (physics + Machine Learning) version of CESM (CESM3MLe)

LEAP

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

M²LInES
Schmidt Futures

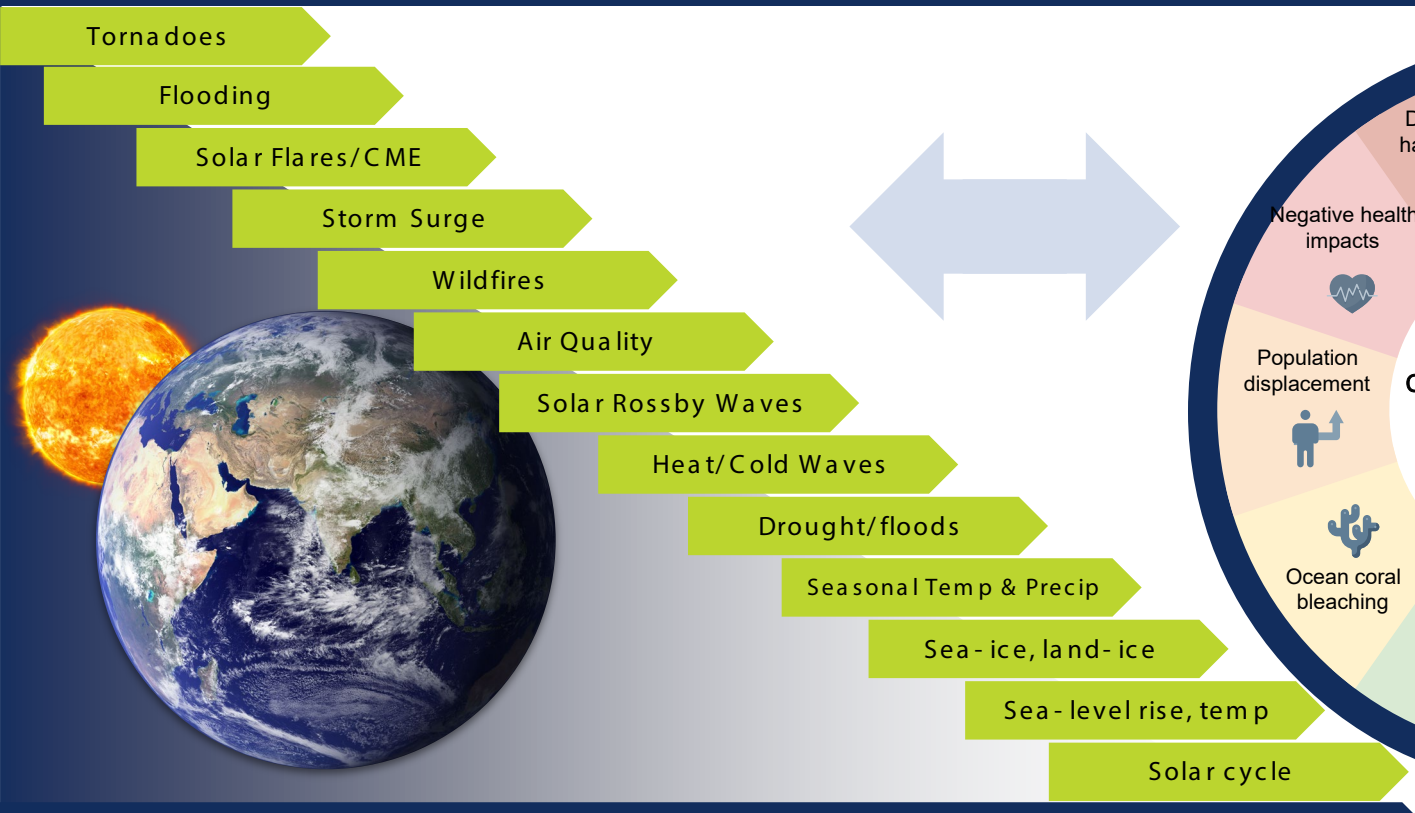


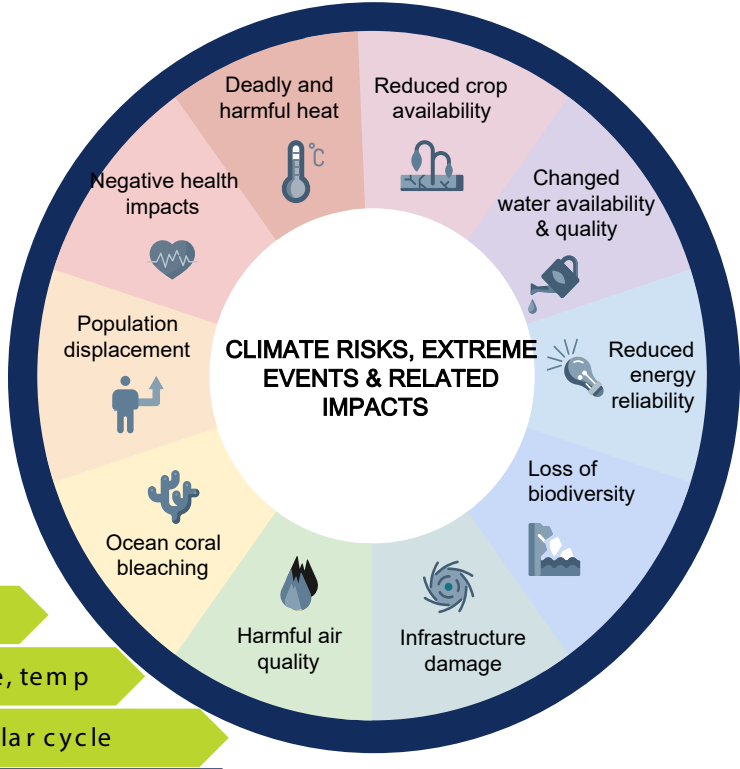
Harness new ML + data to transform CESM

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

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

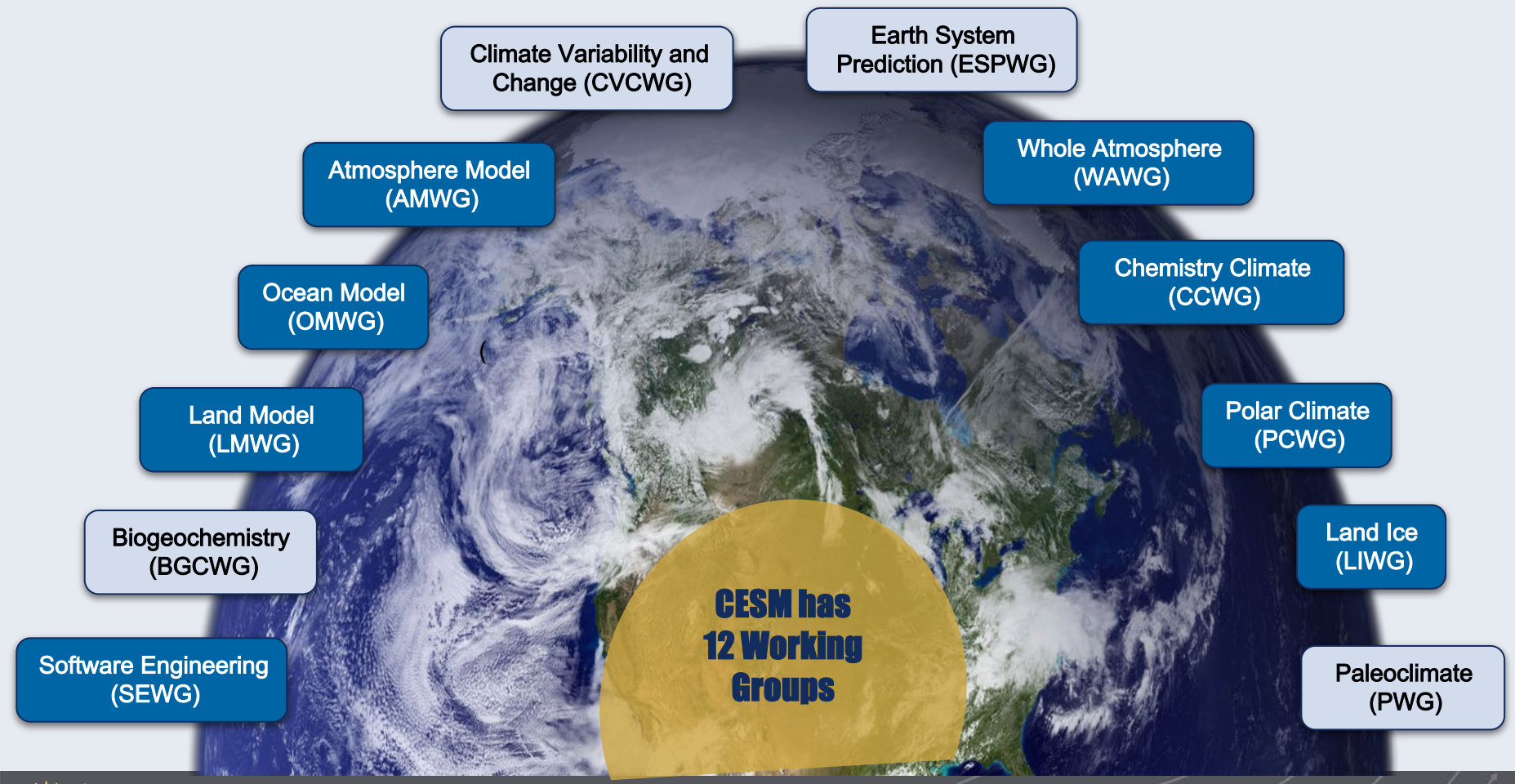
Guided by societal needs, spanning minutes to centuries





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



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!

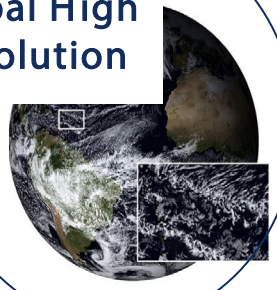
Unified modeling framework

"Pick and Choose" menu of options

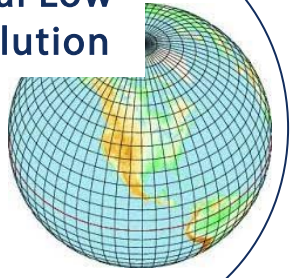
–

All components interact and are ready to play

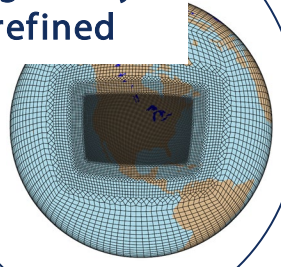
Global High Resolution



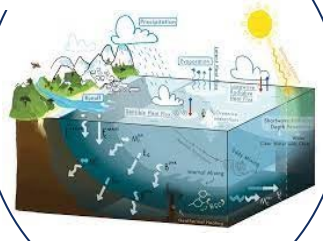
Global Low Resolution



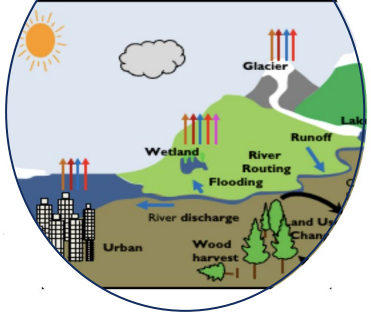
Regionally-refined



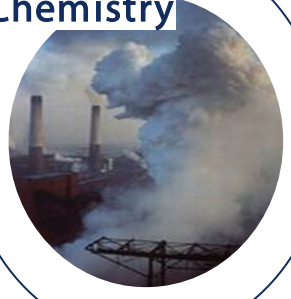
Ocean



Land / Hydrology



Chemistry



Space Weather