

## Earth System Modeling for Actionable Science

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## **Building the foundations of Earth system science**



### **Understand and Predict**

### Share and Explain



### **Actionable** Science

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## **Development of DOE's flagship Energy Exascale** Earth System Model (E3SM) since 2014

### **E3SM** actionable science goals

- High-resolution modeling of extreme weather events in a changing climate
- Represent natural, managed and manmade systems and their interactions to project future outcomes
- Ensemble modeling to quantify uncertainty























Pacific

### Three versions of E3SM have been developed since 2014

Model component	Lower resolution (LR)	High resolution (HR)	Cloud-resolving (SCREAM)	Regional refined model (RRM)
Atmosphere & Land	100 km	25 km	3 km	variable
Ocean & Ice	30-60 km	6-18 km	prescribed	variable
River	50 km	12 km	3 – 12 km	variable

**Human System** 

### **Southern Ocean RRM**





**North America RRM** 



14 km → 60 km













## **Modeling ice shelf-ocean interactions**

### Most climate models



(Asay-Davis, Barthel, Begeman, Comeau, Lin, et al.)



### Melt fluxes in control, two ensemble members of

Antarctica





### **Representing human-Earth interactions**



(Di Vittorio, Calvin, Bond-Lamberty, Sinha, Hao et al.)

### **Evaluate feasibility and impacts of decarbonization scenarios**











## **Global cloud-resolving modeling**

- The Simple Cloud-Resolving E3SM Atmosphere Model (SCREAMv0) was first developed in F90, with the first simulations (40 days) performed on NERSC KNL-Cori
- For performance portability, SCREAM has been rewritten in C++/Kokkos (SCREAMv1) to achieve good performance on NVIDIA, AMD, and Intel GPUs
- First decadal simulations are ongoing on NERSC Perlmutter GPU nodes



### Satellite image

SCREAM simulation

**Clouds and related** processes cause the largest uncertainty in climate modeling





## A model hierachy for scientific discovery

### An E3SM model hierarchy and new capabilities developed by WACCEM















### The first E3SMv1 simulation campaign performed on KNL-Cori

### Achieving energy balance at top-of-atmosphere in pre-industrial simulations







### Model skill comparable to or better than other models



(Golaz et al. 2019 JAMES)









## **Regional refined modeling**

• The first demonstration of fully coupled variable resolution climate simulations performed on Perlmutter, showing mostly positive impacts of increasing grid resolution through regional refinement



(Tang et al. 2023 GMD)



## Predictability of the 2003 European heat wave

Sources of predictability natural and anthropogenic forcing extratropical oceans AMV ENSO soil moisture tronospher century Subseasona Annual to decadal Climate projection

Pacific

Northwest

(Merryfield et al. 2020 BAMS)

A land data assimilation system implemented in E3SM for coupled modeling experiments



With initial conditions produced using land data assimilation, the stationary wave anomalies (heat dome) of the 2003 European heat wave can be predicted 2 years in advance







(Shi et al. in review)







Multi-model ensemble projects increase in intensity and frequency of heat dome-like stationary waves in northwestern North America

> Large data storage at NERSC facilitates analysis of the CMIP6 multi-model ensemble



(Chen et al. 2023 npj CAS)





### **Thunderstorms and their future changes**

- Large, organized convective storms are ubiquitous over the tropical oceans and during the warm season over land
- Modeling these storms, called mesoscale convective systems (MCS), is challenging as high resolution is generally needed to simulate their initiation and development
- They play dominant roles in the climate system and often cause flooding and wind damages









### **Storyline simulations: 2012 North American derecho**



The derecho is realistically simulated by SCREAM at ~3 km resolution



The WRF regional model projects the derecho to have narrower swath and dissipates earlier in the future



(Li et al. 2023 JGRA)







## Storyline simulations: the 2015 TX/OK flood

## The record-breaking TX/OK flood induced by a sequence of MCS storms

# How might the same storms unfold in the future environment?









## **Convective storms, windthrows, and** carbon cycle

Convective storms intensified by global warming may increase windthrows and shift the Amazon basin from a carbon sink to a carbon source in the future

Squall lines account for ~50% of tree mortality across the Amazon basin



Significant increase in squall line area in the future environment



A squall line in January 2005 uprooted trees in large area over central Amazonia. The squall line is well simulated by SCREAM at 3 km resolution



(Xue, Leung, et al.)























### Tracking of mesoscale convective systems (MCS) in observations and simulations

Tracking MCSs using satellite brightness temperature and precipitation (pyFLEXTRKR)



database:

- Cover 60°S 60°N
- Period: 2000-2019
- MCS track masks on native 10 km grid
- MCS track statistics (location, time, lifetime, size, rainfall, etc)
- MCS track data have been combined with ERA5 to provide the environments of the storms
- Data archived at NERSC and accessible through Globus endpoint
- Used by > 40 research groups worldwide

(Feng et al., 2021 JGRA)





### A near global **hourly 10 km** MCS



## The last decade of Earth system modeling facilitated by NERSC

- E3SM model development and testing
- E3SM simulation campaigns and analysis
- Decadal SCREAM simulations
- Predictability experiments, hierarchical simulations, storyline simulations, etc, using E3SM, WRF, CESM, MPAS, and other models
- Data storage and access: CMIP, ERA5, MCS database, ...
- NESAP projects: code optimization, improve performance and workflow
- NERSC provided excellent facilities and logistical support for the E3SM tutorial (May 2024)





### What's next

- Expanding the use of SCREAM for regional and global cloud-resolving modeling, including coupled simulations
- Expand the capabilities for representing human-Earth interactions (e.g., water demand and use)
- Ensemble simulations to understand and quantify uncertainties
- Continue to build the E3SM model hierarchy for scientific discovery (e.g., large eddy simulations of convective storms)
- Leverage AI/ML to improve E3SM and Earth system modeling more generally (e.g., ML parameterizations, model calibration and uncertainty quantification, feature detection and analysis, ensemble modeling)





**Congratulations to NERSC on its 50<sup>th</sup> Anniversary!** 

Thank you for decades of support for Earth system research and modeling!

# 0<sup>th</sup> Anniversary! for Earth



# Thank you

