



E3SM: The Energy Exascale Earth System Model

Phase 2, 2018-2021

The Energy Exascale Earth System Model (E3SM) is a newly developed coupled high-resolution earth system model (ESM). Supported by the U.S. Department of Energy (DOE), it is tailored for energy-relevant research and is designed for DOE high-performance computers.

E3SM Version 1 was released to the broader scientific community in April 2018. It is an open-development project with open source code and is engaging a growing community of scientists.

E3SM PROJECT MISSION, GOAL, AND SCIENCE

E3SM's Mission is to reliably project decade-to-century scale changes that could critically impact the U.S. energy sector. Current focus areas include changes in:

- Water availability for energy production;
- Extreme temperatures which impact the power grid and biogeochemical cycles;
- Energy resource potentials for hydropower, wind, solar and bioenergy; and
- Sea level rise from ice sheets as a result of coupled climate processes.



Figure 1: A high-resolution atmosphere/land grid enables accurate simulation of hurricanes as seen in this high-resolution E3SM Atmospheric component simulation.

E3SM's Goal is to develop an ESM with:

- Better resolution of complex, multi-scale earth system interactions through improved process representations, increased resolution, and enhanced computational performance;
- More realistic representation of the two-way interactions between human and natural processes; and
- Ensemble modeling to quantify earth system uncertainties.

E3SM Science is organized around three simulation campaigns focused on water cycle, biogeochemistry-energy, and cryosphere-ocean research. Each campaign employs unique model configurations optimized to address the associated research challenges, by varying their choice of biogeochemical species, use of variable-resolution gridding, and targeted sensitivity experiments.

The E3SM project built Version 1 with atmosphere and land components based on the Community Earth System Model (CESM). E3SM added new formulations for the ocean, sea-ice, and land-ice components. From there,

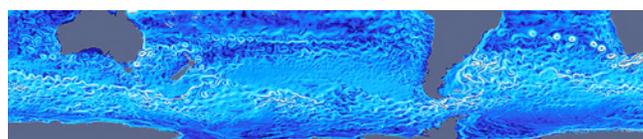


Figure 2: A high-resolution ocean and sea-ice grid is necessary to resolve ocean eddies, depicted here with the high-resolution MPAS Ocean E3SM simulation.

the E3SM atmosphere team improved treatments of clouds, convection, and aerosol-cloud interactions and increased the vertical resolution. Improvements in land hydrology include better representations of water flow in soils and rivers. New ocean, land-ice, and sea-ice component models are based on the variable resolution Model for Prediction Across Scales (MPAS) framework and include improved representations of sea-ice thermodynamics and ocean surface freshwater fluxes.

The “standard resolution” global model includes grid sizes of 100 km for atmosphere/land and variable resolution (30 km at the equator, 60 km at midlatitudes, and higher resolution toward the poles) over ocean and sea-ice regions.

The “high resolution” grid scales are 25 km over atmosphere/land (Figure 1) and 18 to 6 km (from equator to pole) over ocean and sea ice (Figure 2).

All model components (atmosphere, ocean, land, ice) can employ variable resolution, with a smoothly transitioning regionally refined mesh (RRM) to allow more detailed modeling within geographic regions of interest (e.g., Figures 3 and 4).

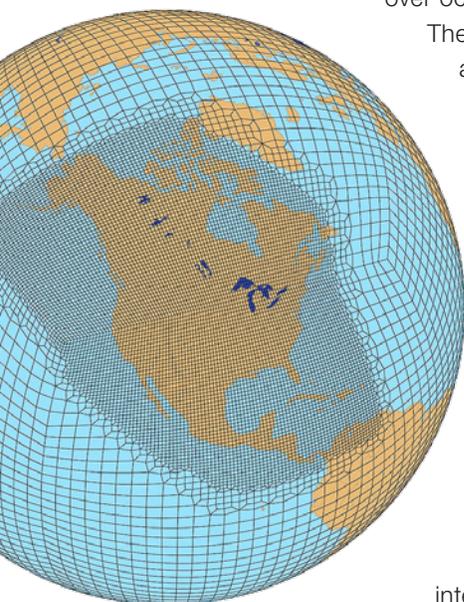


Figure 3: E3SM v2 will utilize a regionally refined mesh configuration over North America and its coastal regions.

WATER CYCLE SIMULATION CAMPAIGN

This campaign—to anticipate changes in water availability and water cycle extremes—investigates interactions between the hydrological cycle and the rest of the human-earth system on local to global scales.

As part of the E3SM v1 water cycle experimental campaign, CMIP6 benchmark “DECK” experiments and a five-member ensemble CMIP6 historical simulation have been completed. This resulted in 1500 simulation years at standard resolution. At high resolution, the project will perform a 50-year 1950 control simulation followed by an ensemble of 1950-2050 simulations, which will be submitted to the CMIP6 High Resolution Model Intercomparison Project ([HiResMIP](#)).

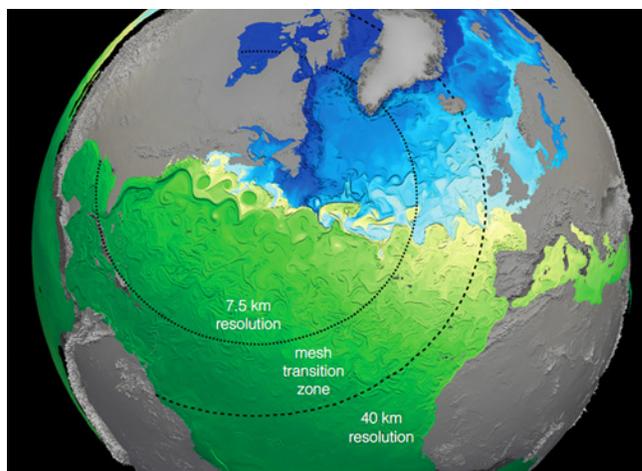


Figure 4: Variable resolution version of MPAS-Ocean.

Experiments with E3SM Version 2 will examine the relative importance of large-scale earth system changes versus local ecosystem and water management on flood and drought risk for North America. Like Version 1, the Version 2 model will utilize RRM, but v2’s RRM will cover a larger area encompassing all of North America and its coastal regions (Figure 3). Model developments include improving parameterization scale-awareness and fidelity for RRM applications and adding new features to represent direct human effects on terrestrial hydrology.

BIOGEOCHEMISTRY-ENERGY SIMULATION CAMPAIGN

This campaign investigates how biogeochemical cycles interact with other earth system components and the implications for the U.S. and international energy systems.

The Version 1 campaign is focused on the interactions of carbon, nitrogen, and phosphorus cycles and their influence on carbon-cycle and climate feedbacks. Model developments include new representations of the phosphorus cycle and nutrient competition. The E3SM v1 simulation campaign includes most of the CMIP6 Coupled Climate-Carbon Cycle Model Intercomparison Project (C4MIP) experiments, covering years 1850-2100 and using the standard resolution model.

Version 2 research will focus on human-natural interactions about land use, water availability, extreme events such as floods and droughts, and how these depend on different energy-use pathways. New developments include improved plant hydraulics, vegetation dynamics, and coupling with the Global Change Assessment Model (GCAM).

CRYOSPHERE-OCEAN SIMULATION CAMPAIGN

This campaign is investigating how rapid changes in the cryosphere (i.e., high latitude ocean, land- and sea-ice systems) evolve and contribute to sea-level rise and increased coastal vulnerability. A particular focus is on resolving the details of Antarctic ice shelf-ocean interactions and their impacts on ice sheet evolution.

The model configuration includes refined resolution on both the periphery of the Antarctic ice sheet and the surrounding ocean (Figure 5). New developments focus on the representation of interactions between climate variability and change, ocean circulation, and melting and freezing beneath the ice-shelves (Figure 6), which impact the ice sheet's dynamics and its contribution to changing sea level.

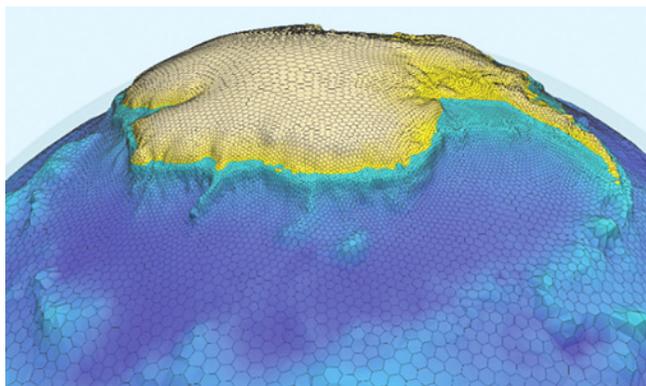


Figure 5: E3SM's cryosphere-ocean simulation model configuration includes refined resolution on both the periphery of the Antarctic ice sheet and the surrounding ocean.

The Version 1 cryosphere-ocean experiments focus on validating modeled climate, ocean, and ice sheet interactions during historical periods and assessing the potential for significant changes in those interactions by 2050. Initial experiments will evaluate the effects of regional mesh refinement on the simulation of Southern Ocean cryosphere systems and on prescribed versus fully coupled atmosphere forcing.

The Version 2 cryosphere-ocean campaign will further investigate the impacts of climate variability on Antarctic ice shelf melting, continental ice sheet evolution and sea-level rise (SLR), and the impacts of changing high-latitude freshwater fluxes on ocean circulation and global climate.

COMPUTATION AND INFRASTRUCTURE

The goal of modeling the coupled atmosphere-ocean-cryosphere-land systems at multi-decadal time scales and high spatial resolution for scientific investigations is

extremely challenging. To meet this objective, it will be essential to realize higher performance and use exascale computer architectures that the DOE Advanced Scientific Computing Research (ASCR) Office will soon procure.

DOE Office of Science has three major computing centers—located at Argonne, Oak Ridge, and Berkeley National Laboratories—which explore multiple exascale computer architecture pathways. The current petascale architectures include multi-core and hybrid CPU-GPU systems. Exascale machines are likely to be even more heterogeneous. E3SM aims to develop code that keeps pace with all of these evolving architectures.

Effective E3SM exascale computing will require groundbreaking innovations on several fronts. These include the development of novel numerical algorithms; programming models to enhance performance portability and task deployment on multiple computer architectures; model restructuring; and extensive code testing. E3SM and its partners are designing new algorithms for faster tracer transport and dynamics, a more extensive task-based approach to model coupling, an atmosphere that subdivides physics and dynamics to use heterogeneous architectures, and a new granular sea-ice model design. New approaches to speed up analysis of the high-resolution model include the use of run-time diagnostics and obtaining statistics from short simulations to test model accuracy. The E3SM team collaborates with CESM developers on the model build and test system and driver through the Common Infrastructure for Modeling the Earth.

FUTURE GENERATIONS OF E3SM: V3/V4

The E3SM project aims for future model generations with major innovations in both model processes and computational performance, and with much higher resolution (e.g., 3 km resolution for the atmosphere).

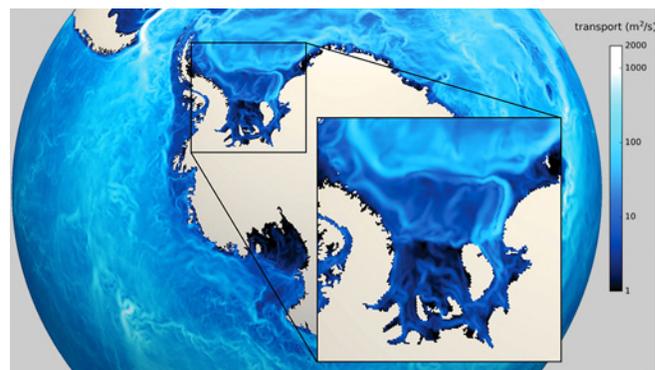


Figure 6: Simulated Southern Ocean transport, including beneath Antarctic ice shelves. Zoom focuses on circulation beneath the Filchner-Ronne ice shelf.

Long-term scientific goals include the ability to capture the statistics of extreme storms such as mesoscale convective systems, coastal features such as biogeochemical changes and inundation due to storm surge and sea-level changes, the projection of land-use and land-cover changes based on socio-economic pathways, dynamic ice sheets as coupled earth system model components, and decadal trends in sea ice.

In support of these goals, new approaches to atmospheric transport, chemistry, radiation, convection, boundary-layer turbulence, and cloud microphysics are under development. The high-resolution atmosphere will use a new non-hydrostatic dynamical core, and the code will migrate from Fortran towards the C++ language.

The land and biogeochemistry treatments will be improved to represent lateral subsurface water flows, more realistic vegetation and terrestrial-aquatic processes. Human energy and agricultural management practices, as well as unmanaged fire disturbances, will be represented.

Ocean and cryosphere advances include the addition of waves and other coastal processes, and two-way coupling of dynamic, variable and adaptive mesh ice sheet models. Critical new ice sheet model physics and their coupling to climate processes will be added. New ocean-eddy transport and vertical boundary layer turbulence schemes will adapt to variable horizontal and vertical resolutions.

E3SM PROJECT ECOSYSTEM AND CODE

The E3SM core project involves coordination among more than 100 scientists from eight DOE national laboratories and several universities. The release of the E3SM v1 model is leading to many new university and laboratory cross-institutional collaborations. Also, model computational work is performed by projects that receive ASCR support, including the SciDAC BER-ASCR partnership projects and ASCR's Exascale Computing Initiative.

PROJECT SUPPORT

The E3SM project is sponsored by Earth and Environmental System Modeling (EESM) within DOE's Office of Science Biological and Environmental Research (BER). The project maintains important collaborations with other BER and ASCR activities.



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E3SM information, code, simulation configurations, model output, and tools to work with the output are available at:

<https://e3sm.org>

Model code may be accessed on the GitHub repository at:

<https://github.com/E3SM-Project/E3SM>

Model output data are accessible through the DOE Earth System Grid Federation at:

<https://esgf-node.llnl.gov/projects/e3sm>

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