AGU Town Hall

E3SM: A Decade of Earth System Modeling Effort at the Department of Energy

Xujing Davis
Asmeret Asefaw Berhe
Gary Geernaert
Dave Bader
Ruby Leung
Mark Taylor
Renata McCoy

E3SM Wins Gordon Bell Prize for Climate Modeling, SC23
Welcome and Introduction
Xujing Jia Davis
DOE ESMD Program Manager
DOE Office of Science Director Perspective:
Role of E3SM for DOE Mission and Science
Asmeret Asefaw Berhe
DOE Office of Science Director
Earth System Modeling Priorities at DOE and Interagency Landscape

Gary Geernaert
DOE EESSD Director

EESSD: Earth and Environmental Systems Sciences Division
Program Overview

Xujing Jia Davis
DOE ESMD Program Manager

ESMD: Earth System Modeling Development Program Area
ESMD in Support of E3SM

Goal: Support the development of E3SM including its subcomponents, to address the grand challenge of actionable predictions of the changing Earth system, emphasizing on the most critical scientific questions facing the nation and DOE

Strategies:
- Science driver for model development
- Earth system across scales (high-resolution frontier, bridge gaps, quantify uncertainty via LE)
- Prepare for and overcome the disruptive transition to next era of computing, leverage ASCR HPC capabilities
- Innovative mathematical, computational methods, tools, algorithms (e.g., ML/AI)

Earth System Across Scales

- Atmosphere
- Ocean
- Land
- River
- Sea Ice
- Human


More E3SM Acronyms: https://e3sm.org/resources/help/acronyms/
ESMD Portfolio & Ecosystem in Support of E3SM

**ES3M**: An integrator of DOE earth, environmental, mathematical and computational sciences, in advancing ESM capability for DOE science mission.

FY 23 Budget Distribution

- **ESMD supported Projects:**
  - Funding instruments:
    - 1. Lab-led projects including Scientific Focus Area (SFAs, e.g., E3SM); 2. Scientific Discovery through Advanced Computing (SciDAC) Awards; 3. Early Career Awards and 4. Other projects: e.g., U. FOA, Interagency activities (e.g, USGCRP/IGIM, CICE Consortium …)
  - **E3SM SFA is the central driver** of the E3SM development with focused scientific questions, well defined time frames, goals and strategies
  - **Other projects contribute to E3SM** development in various ways on different time frames

**E3SM in DOE ecosystem**

**EESSD:**
- **RGMA:** PCMDI, RUBISCO, HYPERFACETS, WACCEM, HILAT-RASM, CATALYST, CASCADE…
- **MSD:** GCIMS (GCAM), HYPERFACETS, IM3 …
- **ARM/ASR:** Field Campaigns, THREADS, LASSO …
- **ESS:** NGEE-Arctic, NGEE-Tropics, SPRUCE, COMPASS-FME, Urban IFL …
- **ASCR:** SciDAC, Exascale Computing Project (ECP) …

**Office of Science:** Energy Earthshot, RENEW, FAIR, RDPP, CRC …

*Note: Univ. scientists across ESMD projects*

See detail about [ESMD Projects](#)

FY 23: $49 M
Science Community Leadership and Service

National
- USGCRP: IGIM US Climate Modeling Summit (USCMS), GEWEX: D. Bader, R. Leung
- NASEM Digital Twin Workshop: R. Leung, M. Taylor
- NCA5: R. Leung, P. Thornton, C. Tebaldi, P. Ullrich
- US CLIVAR: R. Leung
- CESM Advisory Committee: E. Hunke, M. Taylor

International
- CICE Consortium: E. Hunke, A. Roberts
- International CLIVAR: L. Van Roekel
- International Workshop on Coupling Technologies for ESMs: R. Jacob
- WCRP GEWEX Global Atmospheric System Studies Panel (GASS) annual meeting: S. Xie
- Association for Computing Machinery (ACM) and the Swiss National Supercomputing Centre: O. Guba

E3SM contributes to national and global endeavor in advancing Earth System Predictability while addressing the DOE mission
E3SM Timeline and Major Achievements

Approaching its 10th year

- Oct 2014
  Project begins

- Apr 2018
  E3SMv1 Release, open development project

- Sep 2021
  E3SMv2 release, better, faster, RRM; SCREAMv0 developed

- Feb 2023
  SCREAMv1 EAMxx on GPU Frontier

- Dec 2023, Now
  E3SMv3 under testing, expected exciting advancements

- 2026
  E3SMv4, GPU enabled, fully coupled, foundation for Digital Twins

Phase 1
Phase 2
SCREAM: Simple Cloud Resolving E3SM Atmosphere Model
Phase 3
Phase 4

Realizing Exascale vision

- E3SM Unique Capabilities for Actionable Science:
  - Exascale Readiness: developed the 1st benchmark of its kind by running ~3km global simulation SCREAM on Frontier with record setting performance, i.e., the 1st global cloud-resolving model (~3km) to simulate a world’s year of climate in a day
  - RRM – 1st ESM running fully coupled global simulations with RRM in all components (except river), completed climate production simulations
  - Coupled Earth-Human Feedback: coupling with GCAM

E3SM wins Inaugural Gordon Bell - Climate Modeling Prize!

2023 E3SM All-Hands Meeting, Denver, CO
E3SM Leadership Team: Cross Laboratory Initiative

Speakers today

E3SM Executive Committee

- David Bader, Chair
- Ruby Leung, Chief Scientist
- Mark Taylor, Chief Computational Scientist
- Renata McCoy, Project Engineer

**COMPONENT DEVELOPMENT**

- S. Xie
- S. Burrows
- P. Thornton
- G. Bisht
- P. Caldwell
- S. Burrows

**INTEGRATION**

- C. Golaz
- W. Lin
- R. Jacob
- J. Zhang
- S. Sreepathi
- S. Sreepathi

**SCIENCE SIMULATION CAMPAIGNS**

- B. Harrop
- C. Tebaldi
- B. Bond-Lamberty
- J. Holm
- N. Jeffery
- Q. Zhu
- Stephen Price
- Andrew Roberts

*OMEGA: Ocean Model for E3SM Global Applications*

**Atmosphere**

- L. Van Roekel
- E. Hunke
- M. Petersen
- P. Jones

**Land**

- S. Brus
- D. Comeau

**Sea Ice & Land Ice**

- E. Hunke

**EAMxx**

**Performance Coordinator**

- A. Salinger

**ML/AI Coordinator**

- S. Sreepathi
Overview of the E3SM Project
David C. Bader, LLNL
E3SM Council Chair and Lead Principal Investigator
The E3SM Mission: Use exascale computing to carry out high-resolution Earth system modeling of natural, managed and man-made systems, to answer pressing problems for the DOE*.

*The E3SM project's long-term goal is to assert and maintain international scientific leadership in the development of Earth system models that address the grand challenge of actionable modeling and projections of Earth system variability and change, with an emphasis on addressing the most critical challenges facing the nation and DOE.
**E3SM Approach**

- **Major simulations.** A series of simulation-and-projection experiments addressing mission needs with actionable scientific results.

- **Model development.** A well-documented, tested, continuously improving system of model codes that comprise the E3SM Earth system model.

- **Leadership architectures.** The ability to use effectively leading (and “bleeding”) edge computational facilities soon after their deployment at DOE national laboratories.

- **Infrastructure.** An infrastructure to support code development, hypothesis testing, simulation execution, and analysis of results.
E3SM Phase 2 Highlights

- E3SM is possible because of a strong culture of “project before lab,” and the commitment of talented and dedicated scientists, computational scientists and software engineers.
- Completion of v1 Simulation Campaign
- Over 12,000 simulated years of simulations using v2 E3SM
- v2 RRM with consistent model tuning with v2 standard resolution
- Atmosphere algorithmic improvements doubled model throughput
- Demonstrated templated C++ programming model for hybrid CPU/GPU (Exascale) machines that requires little support from compiler vendors
- Established a more rigorous Code Review/Testing process to enable more predictable integration of new developments, both internal and external, eg EAGLES.
- Installed and maintained E3SM system on NERSC and COMPY computers for use by other BER/EESSD programs
The Simple Cloud-Resolving E3SM Atmosphere Model (SCREAM)

• DOE has the fastest computers in the world, but they use NVIDIA, AMD, and Intel GPUs
  • Weather/climate models require major modification to run on GPUs
  • No single programming strategy works for all 3 GPU vendors

⇒ “Performance portability” was needed for E3SM to achieve its exascale ambitions
  • This was achieved by writing a new atmosphere model in C++/Kokkos

• SCREAM won the 2023 Gordon Bell Climate Prize for breaking 1 simulated year per day at $\Delta x=3.25$ km

Fig: throughput vs node count at $\Delta x=3.25$ km on Frontier (AMD GPUs) and Summit (NVIDIA GPUs)
The Phase 3 Concept

Conceptual diagram of parallel development paths
E3SM is on the verge of delivering an Exascale modeling system. What’s next?

• Pushing past past exascale will require ever-more disruptive approaches such as edge computing, machine learning (ML), and next-generation artificial intelligence (AI) to accelerate the fusion of observations and measurements with computing.

• The E3SM project will continuously integrate advanced technologies and Earth system science to deliver capabilities for multi-resolution modeling of the coupled human–Earth system.

• E3SMv4 will be at the center of a connected scientific ecosystem for understanding and modeling the Earth system, and will be the foundation for digital twins of the system and its components.

• DOE will lead in actionable projections of human–Earth system evolution across a broad range of time and spatial scales to support multisectoral decision making and DOE’s energy mission.
E3SM Science
Ruby Leung, PNNL
E3SM Chief Scientist
Overarching goal: advance actionable science in support of DOE’s energy mission

Climate change impacts on energy supply, delivery, and demand

Science drivers:

- Water cycle changes and impacts
- Human-Earth system feedbacks
- Polar processes, sea-level rise, and coastal impacts
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
# Modeling across scales

<table>
<thead>
<tr>
<th>Model component</th>
<th>Lower resolution (LR)</th>
<th>High resolution (HR)</th>
<th>Cloud-resolving (SCREAM)</th>
<th>Regional refined model (RRM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atmosphere &amp; Land</td>
<td>100 km</td>
<td>25 km</td>
<td>3 km</td>
<td>variable</td>
</tr>
<tr>
<td>Ocean &amp; Ice</td>
<td>30-60 km</td>
<td>6-18 km</td>
<td>prescribed</td>
<td>variable</td>
</tr>
<tr>
<td>River</td>
<td>50 km</td>
<td>12 km</td>
<td>3 – 12 km</td>
<td>variable</td>
</tr>
</tbody>
</table>

**CMIP6 DECK, C4MIP**

**HighResMIP**

**DYAMOND**

**CMIP6 DECK (NARRM)**

**North America RRM**

- 25 km ➔ 100 km

**Southern Ocean RRM**

- 14 km ➔ 60 km

**Delaware Bay RRM**

- 4 km ➔ 240 km
Regional refinement: NARRM

NARRM has similar climate sensitivity as LR, simplifying model calibration

- Improved orographic precipitation
- Reduced SWCF bias from stratocumulus
- More realistic tropical cyclone tracks

(Tang et al. 2023 GMD)
A new unified surface mesh over land, river, and ocean

Use of tri-grid and unstructured mesh in all model components provides flexibility for telescoping to the grid spacing needed to model multiple flood drivers and their interactions in coastal regions.
Coupling E3SM-GCAM

**Modeling human-Earth system feedbacks**

**Online coupling** using the coupler enables more dynamic representation of human-Earth system processes

(Di Vittorio, Calvin, Sinha, et al., in prep)
Modeling human-Earth system feedbacks

Water supply and dam regulation schemes

(Floodplain inundation scheme)

(Zhou et al. 2020 JAMES)

Where does water management alleviate future flood

(Luo et al. 2017 GMD)

(Zhou, Leung, et al. in prep)
Modeling polar processes: ice shelf melt fluxes

Most climate models
E3SM

Southern Ocean Regionally Refined Mesh (SORRM) resolution (km)

Configuration:
• Resolution of 12 km in the Antarctic, ~30-60 km elsewhere
• Prognostic ice shelf melt fluxes, data iceberg melt climatology

Melt fluxes in control, two ensemble members of historical and future (SSP370) simulations

C21D-1262 (Asay-Davis et al.) on Tuesday, 9:30am – 1:30pm
Modeling polar processes: Arctic sea ice

Regional Refinement Increases Arctic Sea Ice Volume

Sea Ice Volume \( \times 10^3 \text{ km}^3 \)

Eddy Permitting in the Arctic
E3SM Exascale Readiness
Mark Taylor, SNL
E3SM Chief Computational Scientist
mataylo@sandia.gov
DOE Computing Landscape

• DOE: Large investments in Exascale computing
  • E3SM mission to run on these computers
  • DOE SC machines ranked #1, #2, #7, #12 in the Top500 list of the world’s fastest computers
  • Most of the compute power, power consumption and purchase cost comes from the GPUs

• E3SM Exascale mission = run efficiently on GPUs

• Challenge: GPUs can provide large acceleration of many kernels, but what about the full model, including all the time spent in communication?
  • E3SM’s global cloud resolving atmosphere (SCREAM)
  • 5.8x faster (AMD 2x64 core CPU node vs. 4xA100 GPU node)
  • 3.5x faster per Watt (based on measured power consumption)
Programming Models for GPU systems

- **Fortran + Directives**
  - Relies heavily on (lagging) vendor compiler support
  - Remains immature w.r.t. advanced Fortran features
  - Good performance still requires major code refactoring

- **C++ / on-node Parallel array abstractions (Kokkos and YAKL)**
  - C++ has robust vendor support across NVIDIA, AMD and Intel
  - Kokkos and YAKL backends quickly adapt to each vendor’s preferred technology (CUDA, HIP, SYCL, pthreads, etc…)
  - Kokkos and YAKL rely on standard C++ methodology and work together seamlessly

- **DSL: Domain Specific Language**
  - Promising approach being explored by several modeling centers (e.g. GT4Py, GridTools, PSyclone)
  - Most HPC experience within DOE labs is with C++
E3SM GPU Capabilities

• SCREAM: Simple Cloud Resolving E3SM Atmosphere Model
  • New nonhydrostatic atmosphere model, rewritten from scratch in C++
  • Designed for cloud resolving resolutions (prescribed aerosols, no deep convection parameterizations)
  • Competitive with Fortran version on CPUs, and running well on NVIDIA, AMD (and hopefully soon Intel) GPUs
  • 2023 Gordon Bell Prize for Climate Modeling!

• E3SM-MMF (superparameterized-E3SM)
  • E3SM fully coupled simulations at typical climate resolution, running with most atmosphere parameterizations replaced by a local cloud resolving model
  • GPU acceleration allows MMF approach to obtain similar throughput as a conventional model

• In Progress:
  • Omega: Port of MPAS-Ocean into C++/YAKL
  • ELM: GPU acceleration via Fortran/OpenACC (transitioning to OpenMP to support AMD and Intel GPUs)
GPU enabled simulations
Roadmap

• Cloud resolving atmosphere simulations
  • 2023: Multi-year simulations for Cess-Potter climate sensitivity
  • 2024: Multi-decadal AMIP simulations

• E3SM-MMF
  • 2023: Century long full coupled climate simulations with cloud resolving deep convection “super-parameterization”

• E3SMv4: 2026
  • Full Earth System Model running efficiently on GPUs
  • Atmosphere: based on SCREAM, with additional support for non-cloud resolving resolutions, prognostic aerosols and some chemistry
  • Ocean: Omega eddy resolving ocean
  • Less expensive components (land, Ice): use idle CPU cores of the GPU node, or run on GPUs depending on readiness
E3SM as an Open Science Model Development Project

Renata McCoy, LLNL
E3SM Chief Operating Office & Project Engineer
Open Science Development Model

• E3SM is Open Development Code!!
  • As of the first data release (Apr 2018), E3SM is freely available on GitHub

• All in E3SM tools are open-source development tools
  • [https://e3sm.org/resources/tools/](https://e3sm.org/resources/tools/)

• Data from all major, campaign simulations are available to all, published on ESGF *
  • Few months delay between the production and publication to ESGF to publish an overview paper

• Support for code and data (limited)
  • Support for “scientifically validated” compsets / configuration used in simulation campaigns
  • Supported versions:
    • maint-v1.0, maint-v1.1, maint-v1.2, maint-v2.0, maint-v2.1,
  • Guaranteed to run on the E3SM-supported DOE LC centers

* ESGF – Earth System Grid Federation
Projects can submit a **collaboration request** specifying:

- What data/simulation/early access information they need
- What research are they planning to do
- Specify an E3SM Point of Contact (POC)
- Agree to collaborate and include the E3SM POC in your publication

**Fill in the doc at**

- [https://e3sm.org/about/collaboration/collaboration_request/](https://e3sm.org/about/collaboration/collaboration_request/)
Documentation, Webinars, Online Tutorials

• Extensive documentation on the Confluence public site
  • https://acme-climate.atlassian.net/wiki/spaces/DOC

• Diagnostics and analysis tools
  • https://e3sm.org/resources/tools/

• Documentation and online tutorials
  • https://e3sm.org/about/events/e3sm-tutorials/

• Webinars and presentations
  • https://e3sm.org/about/events/all-hands-presentations/
First In-person Hands-on Tutorial Workshop @ NERSC

- May 7-10, 2024

- At NERSC
  - National Energy Research Scientific Computing Center (NERSC)
  - Lawrence Berkeley National Lab in Berkeley, CA.

- Applications
  - Announce via E3SM and EESSD-related email lists in December
  - Priority to DOE projects
  - https://e3sm.org/announcing-the-e3sm-tutorial-workshop-at-nersc

- The tutorial will encompass:
  1. Lectures on earth system simulation and the model components of E3SM.
  2. Practical sessions on running E3SM, modifying components, and analyzing data.
  3. Best practices for utilizing the model and potentially contributing to its development.

- Will be recorded and available on E3SM YouTube
  - Lectures, examples, class notes
E3SM Communication

- **E3SM Website**  [http://e3sm.org](http://e3sm.org)

- **Public Confluence** for
  - Developer’s documentation: [https://acme-climate.atlassian.net/wiki/spaces/DOC](https://acme-climate.atlassian.net/wiki/spaces/DOC)
  - E3SM Conferences: [https://acme-climate.atlassian.net/wiki/spaces/ECM](https://acme-climate.atlassian.net/wiki/spaces/ECM)

- **E3SM quarterly ”Floating Points” Newsletter** provides:
  - Latest news
  - Research Highlights
  - Project vision and Roadmaps
  - Self subscribe:
    - email listserv@listserv.llnl.gov with the email body: ‘subscribe E3SM-news’

- **E3SM YouTube Channel** with seminars, webinars, and tutorials
  - [https://www.youtube.com/@e3sm-project](https://www.youtube.com/@e3sm-project)
Thank You!
e3sm.org

E3SM-related sessions on AGU: https://tinyurl.com/a8yy958