Decadal Vision (2026–2035)

The goal of the Energy Exascale Earth System Model (E3SM) project is to use cutting-edge scientific and computational technologies to develop a state-of-the-art Earth system model for the U.S. Department of Energy (DOE). During the last 10 years E3SM has created a skillful coupled Earth-energy system model and a world-leading global storm-resolving model which runs on exascale computers. **In the next 10 years, E3SM will leverage breakthroughs in artificial intelligence (AI) and other emerging technologies to develop a trustworthy hybrid physics–AI system for high-resolution Earth system prediction for seasonal to decadal (S2D; 3 months to 10 years) timescales and will use that model to understand the sources of that predictability.** Achieving such capabilities is critical to support science- and technology-informed planning and management of the U.S. energy and water systems, which are foundational to most economic activities and thus vital to our nation's overall economic growth.

Reliable S2D prediction of Earth-system variables critical to efficient operation of U.S. energy and water systems would have substantial benefits for DOE's energy mission. For example, hydrologic predictions months in advance would support reservoir management for hydropower and thermoelectricity production. Simultaneous predictions of temperature, humidity, winds, and cloudiness – which control energy supply and demand - would further aid management decisions, which illustrates the tight coupling between energy and water systems. Anticipating bottlenecks in global shipping due to sea ice, low lake levels, or storms would bring major economic benefit and safeguard the flow of energy to U.S. citizens. Predicting statistical anomalies in weather seasons to years in advance would help optimize bioenergy crop choices and inform resource allocation for hardening energy infrastructure against natural disasters. Extreme events such as hurricanes, cold-air outbreaks, windstorms, heat waves, droughts, floods, ice storms, and wildfires are particularly important to DOE interests because they are the main source of power outages and infrastructure damage, as well as having large impacts on energy supply and demand. Frequency, intensity, and geographic distribution of natural disasters play a central role in determining their impact. These impactful quantities will be our targets for S2D prediction.

Achieving trustworthy S2D prediction remains a grand challenge. Predictability arises from interactions among slowly varying ocean, land, cryosphere, and biosphere states; atmospheric circulation regimes; and coupled teleconnected feedbacks. E3SM's sophisticated physics provides an excellent foundation, but skillful prediction will require improved model accuracy, better initialized states, calibrated ensembles, process-based evaluation, and new methods for extracting interpretable signals from high-dimensional simulations. Improved data assimilation and coupled-model initialization methods will be critical targets in the coming decade. E3SM will leverage DOE investments in AI, uncertainty quantification, and workflow automation to construct a framework for testing and explaining the factors that improve or degrade predictive skill.

E3SM's distinctive advantage is its combination of coupled physics, high resolution, exascale computing, and DOE mission focus. While AI models have rapidly advanced weather prediction (with timescales less than 2 weeks), the significant role of slowly varying Earth system components and their interactions in S2D prediction requires physically grounded representation of ocean, land, cryosphere, atmosphere, and human processes. In particular, sparse observations, limited observational records, and rare events in the coupled system challenge purely data-driven approaches at longer timescales. E3SM will therefore pursue a hybrid strategy: use physically based modeling where processes controlling predictable signals are well represented, and use AI to accelerate, distill, interrogate, and extend the model hierarchy.

High resolution will be used strategically to determine where finer grids change predictive skill. To provide a high-resolution baseline for this analysis, E3SM will target 1–10 km grid spacing in all components by the end of this decade. The team believes that such fine resolution is needed to accurately model important phenomena such as hurricanes and orographic precipitation in the atmosphere, river channels and groundwater exchange in soil, sea-ice dynamics and ice-sheet outlet regions in the cryosphere, and eddies and coastal passages in the ocean.

Science Drivers

Two overarching science questions will be addressed in the next decade:

1. **What are the mechanistic sources of predictability for DOE-relevant Earth-system phenomena at seasonal, annual, and decadal scales?** E3SM will use ensembles as a controlled laboratory for determining which initial states, modes of variability, coupled pathways, and reservoirs of heat and freshwater affect forecastable signals as well as diagnosing how sources of predictability shift at seasonal, annual, interannual, and decadal lead times. AI will be used to identify causal relationships between sources for and targets of predictability across S2D lead windows. Besides clarifying the mechanistic pathways of well-known sources of predictability, E3SM's hallmark capabilities of high-resolution and coupled human-Earth system modeling open unique opportunities to investigate under-explored sources of predictability associated with fine-scale processes such as mesoscale ocean eddies, mountain processes, and coupled human-Earth system dynamics.

2. **How do choices in model design and configuration alter the predictable signals and internal variability of the coupled system to improve Earth system predictability?** For energy-relevant Earth system hazards, E3SM will ask how added resolution and model formulation changes predictable signals and internal variability by altering the representation of key sources of Earth-system memory and coupled feedbacks as well as by better capturing connections between large-scale predictable states and local impacts. Using emulators to create huge ensembles will be important for precisely separating predictable signals from internal variability.

These science questions will be evaluated across the target energy-relevant phenomena. For each phenomenon, E3SM will identify sources of predictability, lead windows, model-resolution requirements, AI opportunities, verification metrics, and energy-relevant derived quantities. More specific science questions will be developed in each project phase, each supporting the same objective: to deliver a skillful Earth system prediction capability through a virtuous cycle of model development and evaluation via simulation campaigns to understand why E3SM has probabilistic skill, why it loses skill, when dominant sources of predictability change, and which compound Earth-system pathways produce useful information for the U.S. energy complex. This understanding will inform new development. Progress will be tracked via a dashboard containing key metrics of model performance for each model release.

Computational Focus

Ultra-high-resolution, physics-based simulations enabled by exascale computing will continue to be important to E3SM since S2D prediction lacks sufficient observations for training. Science breakthroughs of this decade, however, will be powered by AI and (eventually) quantum computing. AI already infuses every aspect of E3SM, and the team has identified six areas where it will be transformative:

1. **AI component and full-model emulators** enable large enough ensembles to map the entire envelope of outcomes from a chaotic coupled system, rather than the handful of trajectories high-resolution physics-based modeling can afford. The same speedup can also be used to efficiently explore the coupled-model impact of changes to one component by emulating the rest. Ability to reproduce the characteristics of E3SM physics-based components at low computational cost will be critical for understanding and characterizing S2D predictability.
2. **Machine-learned parameterizations** offer a path to greatly accelerate the historically slow progress of Earth system model improvement caused by persistent errors in representing sub-grid scale processes. Running extremely sophisticated process models at very fine resolution remains out of reach for global models, but learning their representation with advanced AI architectures is promising and forms the core of E3SM's hybrid physics–AI plans.
3. **AI-based data assimilation** gives E3SM a key new capability to improve S2D prediction. Working with other DOE projects, generative AI for data assimilation offers a path to fuse sparse, heterogeneous, and spaceborne observations into well-balanced initial E3SM states more efficiently and effectively than traditional methods. Investing in data assimilation techniques is a priority for S2D prediction due to the importance of the initial and boundary conditions.
4. **Autotuning calibration** replaces time-intensive, artisanal, subjective tuning with objective, continuous, and automated tuning. With an autotuning framework in place, isolated processes and coupled components will be retuned regularly whenever their codes are updated. The autotuning framework will include transparent metrics that are tracked and shared widely as the software evolves.
5. **AI-enabled workflow automation** frees the team to focus on the hardest problems rather than busywork best handled by autonomous agents. Automated tools for writing documentation and configuring, running, and monitoring simulations and analysis will help reduce human error.
6. **AI pattern recognition** mines the high-dimensional output space of E3SM's carefully curated and constructed simulations and emulations for low-dimensional relationships carrying S2D predictability. Representation learning and reduced-order methods will distill the output space into compact, interpretable source–target relationships to be tested.

Together, these capabilities form a discovery loop greater than the sum of its parts. Data assimilation enables initialization of the model from observations; high-resolution physics-based simulations provide a trustworthy foundation and emulators expand them into ensembles large enough to expose robust signals; pattern recognition distills the signals into candidate mechanisms as falsifiable hypotheses; these ideas are then tested in the hybrid physics–AI model by enhancing or suppressing suspected pathways. What survives is folded back into the next model as a machine-learned parameterization, a resolution choice, or a better initialization; the next model is calibrated and the process starts again. This loop turns raw computations into an instrument not just for S2D prediction, but for understanding why.

Beyond AI, E3SM will continue to position itself to exploit DOE's HPC, including quantum computing. A promising use case of quantum computing in Earth system modeling is to resolve, rather than parameterize or emulate, critical small-scale processes such as cloud microphysics and turbulence. Consistent with its longstanding role as an integrator of proven technology rather than a venue for high-risk hardware exploration, E3SM will prepare for the quantum era by partnering with ASCR, LDRD, and other efforts, standing ready to adopt quantum capabilities as they mature.

Relationship to Other Projects

E3SM will provide the DOE research community with a world-class high-resolution Earth system model hierarchy along with simulation output, enabling partner projects to initialize their own local models, explore hypotheses, and conduct novel analyses. Because E3SM's primary stakeholders are DOE researchers, direct contact with organizations using Earth system data to make real-world decisions will be left to DOE's more applied projects. E3SM will remain connected to applications by coordinating with DOE partners on target variables, derived diagnostics, verification protocols, and uncertainty measures. The team also partners with other DOE projects and technology companies to integrate mutually beneficial code into the E3SM codebase, enabling other teams to extend the reach and impact of their work. A users' group and structured engagement process will identify opportunities for improvement and synergy as well as ensuring E3SM meets the needs of relevant projects.

Outcomes

As a DOE Office of Science project, E3SM's goal is to deliver scientific discoveries and enabling tools to transform our understanding of nature and advance the energy, economic, and national security of the U.S. To do this, the project will develop a high-resolution hybrid physics–AI Earth-system modeling capability with world-leading S2D skill and will use this system to identify, understand, and improve model representation of the mechanisms that lead to probabilistic prediction skill. In particular, the team will deliver a model hierarchy for testing where resolution changes forecastable signals and a trustworthy AI framework for discovering sources of predictability and translating them into a structured set of energy-relevant prediction targets and metrics. Achieving this vision will require improved process representation, better initialized states, larger and more informative ensembles, rigorous verification, careful calibration, and disciplined use of AI and other advanced technologies. By focusing on variables relevant to energy supply, demand, infrastructure, and reliability, E3SM will provide the scientific basis for improved U.S. energy security, resilience, affordability, and competitiveness in a complex world.