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INTRODUCTION TO A SPECIAL SECTION

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Special Section:

The Energy Exascale Earth System Model (E3SM)

Key Points:

- The Energy Exascale Earth System Model (E3SM) project aims to improve actionable predictions of Earth system variability and change
- Water cycle, biogeochemistry, and cryosphere systems are the three key science drivers of model development and numerical experiments
- This paper provides an overview of the E3SM project and introduces the E3SM special collection of papers published in AGU journals

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Abstract Supported by the U.S. Department of Energy (DOE), the Energy Exascale Earth System Model (E3SM) project aims to optimize the use of DOE resources to address the grand challenge of actionable predictions of Earth system variability and change. This requires sustained advancement to (1) integrate model development with leading-edge computational advances toward ultra-high-resolution modeling; (2) represent the coupled human-Earth system to address energy sector vulnerability to variability and change; and (3) address uncertainty in model simulations and projections. Scientific development of the E3SM modeling system is driven by the simulation requirements in three overarching science areas centering on understanding the Earth's water cycle, biogeochemistry, and cryosphere systems and their future changes. This paper serves as an introduction to the E3SM special collection, which includes 50 papers published in several AGU journals. It provides an overview of the E3SM project, including its goals and science drivers. It also provides a brief history of the development of E3SM version 1 and highlights some key findings from papers included in the special collection.

Plain Language Summary Earth system models are important tools for predicting future changes in the Earth system. Supported by the U.S. Department of Energy (DOE), the Energy Exascale Earth System Model (E3SM) project aims to improve predictions of Earth system variability and change. The latter has a particular focus on predicting changes in the water cycle that influences precipitation and storms, biogeochemistry that influences greenhouse gases and future warming, and cryosphere systems that influence sea-level rise that threatens coastal communities. This paper serves as an introduction to the E3SM special collection, which includes 50 papers published in several AGU journals. It provides an overview of the E3SM project, including its goals and science drivers. It also provides a brief history of the development of E3SM version 1 and highlights some key findings from papers included in the special collection.

1. Introduction

In 2011, the U.S. Department of Energy (DOE) developed a report summarizing observed long-term trends that, if continued in the future decades, would have major impacts on the energy sector (Department of Energy, 2013). Among these were regional trends in air and water temperatures, water availability, storms and heavy precipitation, coastal flooding, and sea-level rise. The ability to simulate and predict significant, long-term changes in these environmental variables important to energy-sector decisions required capabilities beyond the existing state-of-the-science Earth system models running on the most powerful petascale computers at the time. Concurrently, DOE developed the Exascale Initiative, "a major computer and computational science initiative anchored in (DOE's) mission challenges.... to capture the successful transition to the next era of computing in the 2020 timeframe," while noting that "due to projected technology constraints, current approaches to high performance computing (HPC) software and hardware design will not be sufficient to produce the required exascale capabilities."

The DOE Energy Exascale Earth System Model (E3SM) project (http://e3sm.org) was conceived from the confluence of energy mission needs and disruptive changes in scientific computing technology. Developed as a state-of-the-science Earth system modeling project, E3SM aims to optimize the use of DOE resources to meet the science needs of DOE. The long-term goal of the E3SM project is to address the grand challenge of actionable predictions of Earth system variability and change, with an emphasis on the most critical scientific questions facing the nation and DOE. Addressing the grand challenge requires sustained advancement to (1) integrate model development with leading-edge computational advances toward ultra-





high-resolution modeling; (2) represent the coupled human-Earth system to address energy sector vulnerability to variability and change; and (3) address uncertainty in model simulations and projections.

Scientific development of the E3SM modeling system is driven by the simulation requirements in three overarching and interrelated science areas that are foundational for advancing Earth system science and addressing DOE's need to understand and prepare for future variability and changes in Earth system properties critical to the energy sector such as water availability, storm severity, air and stream temperature, coastal flooding, and sea-level rise. We pursue three overarching science questions centered on the Earth's water cycle, biogeochemistry, and cryosphere systems:

- 1. (*Water cycle*) How does the hydrological cycle interact with the rest of the human-Earth system on local to global scales to determine water availability and water cycle extremes?
- 2. (*Biogeochemistry*) How does the biogeochemical cycle interact with other Earth system components to influence energy-sector decisions?
- 3. (*Cryosphere systems*) How do rapid changes in cryosphere systems evolve with the Earth system and contribute to sea-level rise and increased coastal vulnerability?

The E3SM project is executed through four intersecting project elements: (1) a well-documented and tested, continuously advancing, evolving, and improving system of model codes that comprise the E3SM Earth system model; (2) a series of prediction and simulation experiments addressing scientific questions and mission needs; (3) the ability to use effectively leading (and "bleeding") edge computational facilities soon after their deployment at DOE national laboratories; and (4) an infrastructure to support code development, hypothesis testing, simulation execution, and analysis of results.

During the first phase of the project (2014–2018), the E3SM team developed its first model version (E3SM v1). This special collection documents the development and evaluation of E3SM v1, modeling experiments using E3SM v1 to address aspects of the project's science questions, and some new development toward E3SM v2. A total of 50 papers are featured in this special collection. A majority of the papers document the development, evaluation, and analysis of individual atmosphere, ocean/ice, and land/river components of E3SM. In addition, several papers describe the coupled model configurations and evaluations to address science questions related to water cycle and biogeochemistry. In this introduction to the special collection, a brief history of the E3SM development is given in section 2, highlights of modeling challenges and simulation results are provided in section 3, and section 4 concludes with brief remarks.

2. A Brief History of E3SM Development

E3SM v1 was developed on the foundation of the Community Earth System Model version 1 (CESM1) (Hurrell et al., 2013; http://www.cesm.ucar.edu/models/cesm1.0), sponsored by the U.S. National Science Foundation and DOE. CESM1 was brought into the E3SM Github and served as version 0 of E3SM. While the Community Atmosphere Model (CAM5) and Community Land Model (CLM4.5) of CESM1 were adopted in E3SM v1 with structural changes, the ocean, sea ice, and land ice components of CESM1 were replaced by new models based on the Model for Prediction Across Scales (MPAS) framework (Ringler et al., 2010, 2013). The river component of CESM1 was also replaced by a more physically based model, Model for Scale Adaptive River Transport (MOSART) (Li et al., 2013; Li, Leung, Getirana, et al., 2015). As in CESM1, data exchange among the six model components is accomplished using a flux coupler, which allows simulations to be performed in a fully coupled mode or with subsets of the component models forced by data passed from the coupler (Figure 1).

E3SM Atmosphere Model (EAM v1) uses the spectral element dycore rather than the default finite volume dycore used in CAM5 in CESM1 that it branched from because of its superior computational performance. Cloud microphysics, shallow convection, and turbulence parameterizations were replaced, the aerosol parameterization was enhanced substantially (Wang et al., 2020), and the vertical resolution was increased from the standard 30 levels with a top at ~40 km in CAM5 to 72 levels with a top at ~60 km in EAM (Rasch et al., 2019). Increasing the vertical resolution is important as E3SM targets ultra-high resolution in its development path, so the vertical resolution must increase commensurably with the increase in horizontal resolution.





Energy Exascale Earth System Model

Figure 1. The atmosphere, land, river, ocean, sea ice, and land ice components of E3SM and their coupling.

Building from CLM4.5, E3SM Land Model (ELM v1) includes new options for representing soil hydrology and biogeochemistry, featuring a variably saturated flow model (Bisht et al., 2018) and a new module for phosphorus dynamics (Yang et al., 2019). To understand the effects of nutrient limitations on carbon-climate feedbacks and their sensitivity to model structural uncertainty, two biogeochemistry approaches are included in ELM v1 to contrast a mechanistic (Equilibrium Chemistry Approximation or ECA; Tang, 2015; Tang & Riley, 2017; Zhu et al., 2016, 2017) and a conceptual (Converging Trophic Cascade or CTC; Duarte et al., 2017; Mao et al., 2016; Raczka et al., 2016) framework for representing nutrient competition between microbes, plants, and abiotic processes. The MOSART river model replaces the River Transport Model (RTM) used in CESM1 as the river component of E3SM. MOSART can operate on regular latitude-longitude grids or watersheds as the computational units (Li et al., 2013; Tesfa et al., 2014). With a more physically based representation of river routing at hillslope, tributary, and main channel, MOSART was designed to be extensible for modeling riverine water, energy, and biogeochemistry in Earth system models.

MPAS ocean (MPAS-O) (Petersen et al., 2019), sea ice (MPAS-SI) (Petersen et al., 2019), and land ice (MPAS-LI) (Hoffman et al., 2018) uses spherical centroidal Voronoi tessellations (SVTs) for multiresolution modeling, which is important for addressing cryosphere questions related to Arctic and Antarctic processes. The multiresolution framework also lays the foundation for future development to represent coastal processes that are often ignored or oversimplified in Earth system models. Within E3SM, MPAS-O was used for the first time in a fully coupled modeling framework. Three major development efforts were completed during Phase 1: extending the ocean domain to include ice shelf cavities around the Antarctic Ice Sheet (Asay-Davis et al., 2017), verifying and validating the KPP scheme (van Roekel et al., 2018), and developing an online, scalable, high-performance implementation of Lagrangian particle trajectories to study mesoscale-induced mixing (Wolfram & Ringler, 2017a, 2017b).

Coupling the new MPAS ocean, sea ice, and land ice models on Voronoi grids, the MOSART river model on lat/lon or watershed grids (Tesfa et al., 2014), and EAM and ELM on spectral element grids through a flux coupler, E3SM v1 features a unique capability for multiresolution modeling using unstructured grids in all of its component models. This capability will provide critical support for high-resolution (HR) simulations using regional refinement to meet DOE's needs for Earth system modeling in support of energy-sector decisions. Regional refinement meshes have been used in Phase 1 for testing atmospheric physics parameterizations for HR modeling (Tang et al., 2019) and in ocean/ice simulations over Antarctica for developing capabilities to model ice shelf-ocean interactions. Regional refinement meshes with higher resolution over North America (Hoch et al., 2020) and Antarctica will be used prominently in future simulations using E3SM v2.

E3SM v1 has been tested and evaluated in two configurations at low resolution (LR), also called the standard resolution, and HR. At LR, EAM and ELM are applied on a spectral element grid (ne30) at ~100 km grid spacing. MPAS ocean and sea ice operate on a Voronoi grid with grid spacing varying between 30 and 60 km. MOSART runs on a lat/lon grid at 0.5° grid spacing. At HR, EAM and ELM run on a spectral element grid (ne120) at ~25 km grid spacing. The MPAS ocean and sea ice models run on a Voronoi grid with grid space space





Figure 2. Throughput in SYPD for each component (ATM, atmosphere; OCN, ocean; ICE, ice) of the high-resolution v1 configuration on Cori-KNL nodes. All components scale well; the ocean and ICE scale better than their v0 counterparts.

spacing varying between 6 and 18 km. MOSART runs on a lat/lon grid with a grid spacing of 0.125°. These two configurations at LR and HR are described in Golaz et al. (2019) and Caldwell et al. (2019), respectively. Constrained by computing resources needed for long model spinup and increased model complexity, simulations with biogeochemistry adopt the LR configuration (Burrows et al., 2020).

A comprehensive infrastructure has been developed from scratch for code management, development, testing, and analysis to enable the development of E3SM v1 and future versions on DOE Leadership Computing Centers. Leveraging DOE investments, a flexible framework has been developed to provide workflow orchestration, provenance capture and management, simulation analysis and visualization, and automated testing and evaluation capabilities. Despite the significant increase in complexity in v1 relative to v0, the throughput of the model has stayed roughly the same. This was enabled through 3–4X performance improvement achieved by profiling code, improving algorithms and communications, using nested threading and vectorization, and tuning of parallel I/O.

In particular, a great deal of effort was spent to get the E3SM model performing optimally on the new Knight's Landing (KNL) architecture. After this work, the E3SM components scale very well, as shown in Figure 2. Using 64 MPI tasks and 2 OpenMP threads per KNL node, this

figure demonstrates that the model is able to run efficiently up to ~172 k threads in the atmosphere and ~64 k threads in ocean/ice. The MPAS ocean and ice components in v1 have dramatically improved scaling compared to the v0 ocean/ice models (POP/CICE). To support the simulation campaigns, the processor layout was tuned to achieve optimal throughput for the coupled system. On Cori-KNL, the 825-node configuration for HR achieves ~1 simulation year per day (SYPD) and costs 1.2 million (M) core-hours per simulated year.

To facilitate rapid model development and performance testing, significant efforts were put into developing and supporting computational infrastructure (Figure 3). Building on the framework described in Williams (2016), the infrastructure includes code and data management, automated testing, and standard timing and profiling tools with performance capture and archiving capability. All simulations using the E3SM model automatically capture detailed performance information that is collected and archived in a specific location on each of our production platforms. This database has proven very useful in diagnosing performance bottlenecks as well as machine anomalies so optimal processor layouts can be created and analyzed for production simulations. The infrastructure also includes a diagnostic component that enables the generation of evaluation and diagnostic plots substantially equivalent to the CESM AMWG and LMWG diagnostics while adding new capabilities for comparison of model simulations with many different and newer observational data sets, as well as new model diagnostics using the extended UV-CDAT framework called the Community Diagnostics Package (CDP). Significant new and performance-enhancing functionalities were added to the NCO package, which is critical for E3SM diagnostics efforts and is heavily used for generating climatologies and performing regridding. Other infrastructure developments include testing and deployment procedures on all E3SM-supported platforms and integration of external diagnostics packages and libraries such as the International Land Model Benchmarking (ILAMB) via Common Infrastructure for Modeling the Earth (CIME), Atmospheric Radiation Measurement (ARM) diagnostics, and the Program for Climate Model Diagnostic and Intercomparison (PCMDI) Metrics Package (PMP) (Gleckler et al., 2016). Additionally, the infrastructure includes Process Flow, a smart, distributed, and asynchronous job scheduling tool that automatically initiates, orchestrates, and executes a wide range of backend services like data transfer and diagnostics.

3. Highlights of Modeling Challenges and Simulation Results

As discussed in section 1, E3SM model development is primarily driven by the need to address science questions related to the water cycle, biogeochemistry, and cryosphere systems in support of DOE's missions.





Figure 3. The E3SM postprocessing infrastructure includes several diagnostic suites and visualization software, provenance capture and data management with archive and publication to ESGF.

Hence, in developing E3SM v1, major efforts were devoted to improving the modeling of water cycle, biogeochemistry, and cryosphere processes. This special collection highlights important efforts devoted to improving the modeling of water cycle processes particularly related to clouds, precipitation, and terrestrial hydrology, and biogeochemical processes in the terrestrial component. While physical and biogeochemical processes in the ocean and ice have a dominant influence on the water cycle, biogeochemical cycle, and cryosphere systems, these model components are not a major focus of this special collection, although some aspects of ocean/ice modeling are discussed (Hoffman et al., 2019; Petersen et al., 2019; van Roekel et al., 2018). In what follows, we highlight some challenges in modeling the water cycle and biogeochemistry and insights from model simulations, focusing particularly on efforts documented in this special collection.

3.1. Water Cycle Modeling

The E3SM v1 model development for the water cycle driver was motivated by our science question: "How will more realistic portrayals of features important to the water cycle affect simulations of river flow and associated freshwater supplies at watershed scale?" This question prompted attention to address common biases in modeling water cycle processes, add new capabilities to represent missing processes in the models, and evaluate sensitivity to model resolutions and parameters associated with the water cycle.

Clouds and precipitation are key elements of the water cycle, which is also tightly coupled with the energy and biogeochemical cycles. Overall improvement in modeling clouds and precipitation in EAM v1 is attributed mainly to the introduction of a simplified third-order turbulence parameterization, Cloud Layers Unified By Binormals (CLUBB), which unifies the treatment of boundary layer turbulence, shallow convection, and cloud macrophysics (Xie et al., 2018). However, model performance is sensitive to both horizontal and vertical resolutions as well as model parameter values. These challenges are discussed prominently in several papers in this special collection (Caldwell et al., 2019; Qian et al., 2018; Rasch et al., 2019; Xie et al., 2018). For example, Xie et al. (2018) found that improvement from the use of CLUBB and the increased vertical resolution from 30 to 72 levels can be offset by retuning of model parameters to achieve top-of-atmosphere energy balance. Furthermore, without retuning of model parameters, increasing horizontal resolution from ~100 to ~25 km degraded the simulation of clouds and precipitation, indicating the need to improve scale awareness of the cloud parameterizations. Using a large number of short simulations in a perturbed physics ensemble, Qian et al. (2018) identified the most sensitive parameters from among 18 parameters related to the turbulence, convection, and cloud microphysics parameterizations for simulating the global mean and spatial distribution of clouds, precipitation, and radiation. Their results highlighted the challenge of simultaneously reducing biases in multiple variables using parameter tuning.



As implicated by Qian et al. (2018) and other uncertainty quantification studies, model structural uncertainty is a key factor limiting the potential for reducing model biases through parameter tuning. A longstanding bias of weather and climate models is the diurnal variability of precipitation, which has proven to be difficult to address by tuning parameters alone. Xie et al. (2019) tested two modifications to the cumulus parameterization scheme in EAM v1 to prevent convection from being triggered too frequently and to capture nocturnal elevated convection. These changes substantially improved the diurnal cycle of precipitation simulated over land in both the midlatitudes and the tropics. Another persistent bias common in many models is the underestimation of summer-time precipitation in the Tropical West Pacific, where convection occurs under light surface winds. Harrop et al. (2018) implemented a convective gustiness parameterization in EAM to account for the effect of convective gustiness on evaporation and precipitation. Including the missing process reduced the precipitation bias in the Tropical West Pacific by increasing evaporation from the surface. Including the impacts of aerosols on cloud microphysical processes also has significant influence on the EAM simulation of clouds, particularly stratiform and shallow convective clouds (Wang et al., 2020). These examples aside, parameter tuning can effectively improve the modeling of some specific processes. For example, with the higher model top in EAM, tuning of a parameter associated with the parameterization of convectively generated gravity wave was demonstrated to improve the simulation of quasi-biennial oscillation (QBO) (Richter et al., 2019), which has wide-ranging influences on tropospheric variability and extratropical storm tracks, with implications for the water cycle. These new development and model tuning are being integrated and evaluated in combination with other model changes for EAM v2.

For terrestrial water cycle processes, model development has focused mainly on including missing processes in the model. A particular emphasis has been on representing the impacts of human activities such as irrigation and water management on water fluxes and storages. E3SM v1 features a new river transport model, MOSART, which was designed as a framework for modeling riverine water, heat, and biogeochemical fluxes across scales (Li et al., 2013; Li, Leung, Tesfa, et al., 2015). Building on this framework, Li, Leung, Tesfa, et al. (2015) described a new stream temperature module in MOSART, which provides an important capability for relating water availability to thermoelectric power generation (Zhang et al., 2020). MOSART also serves as a conduit for representing irrigation and water management. Leng et al. (2017) extended the irrigation scheme in CLM4.5 to account for the sources of irrigation water (surface water vs. groundwater) and the methods of irrigation (sprinkler, drip, and flood) in ELM and differentiated their distinct water use efficiency and impacts on runoff and groundwater recharge. Voisin et al. (2017) enhanced the water management model that has been coupled with ELM and MOSART (Voisin et al., 2013) with spatially distributed allocations of sectoral water demands. Zhou et al. (2020) developed two-way coupling between ELM and MOSART with water management to constrain the irrigation amount by water available in the streams and reservoirs. Mao et al. (2019) evaluated a MOSART floodplain inundation parameterization (Luo et al., 2017) globally and studied flood generation mechanisms and their historical changes. The stream temperature, water management, and floodplain inundation modules, as well as the two-way coupling of ELM and MOSART with irrigation and water management, are being integrated into E3SM v2 for enhanced capabilities to represent human-Earth system interactions.

Using the LR configuration, simulations have been performed with the coupled E3SM v1 following the Coupled Model Intercomparison Project Phase 6 (CMIP6) Diagnostic, Evaluation and Characterization of Klima (DECK) experimental protocol (Eyring et al., 2016). The goal is to establish the scientific credibility of E3SM v1, including its overall climate and hydrological cycle, by using a common protocol that allows comparison with other CMIP6 models. Golaz et al. (2019) compared some key aspects of the coupled E3SM historical simulations at LR with observations and the CMIP5 simulations. Overall, E3SM v1 demonstrates significant improvements in model skill compared to the CMIP5 models, as measured by the root mean square errors of nine variables at seasonal and annual time scales. In the historical simulations, the model captures the bulk of the observed warming between preindustrial (1850) and present day, but a period of delayed warming followed by excessive warming is obvious in the second half of the 20th century. Using a two-layer energy balance model, Golaz et al. (2019) attributed the discrepancy from the observed warming trends to the model's strong aerosol-related effective radiative forcing (ERF_{ari + aci} = -1.65 Wm⁻²) and the high equilibrium climate sensitivity (ECS = 5.3 K). The latter was further attributed to a larger positive cloud feedback compared to the median of the CMIP5 models, which may be partly related to more supercooled liquid produced by EAM compared to most CMIP5 models (Zhang et al., 2019). Other aspects of the DECK



simulations analyzed and reported in this special collection include the ocean barrier layer (Reeves Eyre et al., 2019), stratocumulus clouds (Brunke et al., 2019), and monsoonal water cycle (Harrop et al., 2019).

Besides the DECK simulations at LR, E3SM v1 has also been run using both the LR and HR configurations following the CMIP6 HighResMIP experimental protocol (Haarsma et al., 2016). Comparison of the LR and HR simulations allows our science question of the impacts of model resolution on the realism of the water cycle and subsequent influence on water availability to be addressed. Caldwell et al. (2019) summarized the HR and LR configurations used in HighResMIP, noting some differences in parameterizations and model tuning compared to the LR configuration used in the DECK experiments (Golaz et al., 2019). Results from the control simulations with 1950 forcing showed that overall, model biases in terms of global root-mean-square errors are reduced in the HR simulation relative to the LR simulation. Ocean and sea ice simulation is particularly improved, but certain features such as stratocumulus and the El Niño Southern Oscillation are rather insensitive to model resolution. Besides large-scale features, Caldwell et al. (2019) also evaluated and compared many aspects of the LR and HR simulations to highlight the impacts of model resolution. Examples include tropical cyclones, orographic and extreme precipitation, and clouds and aerosols that often exhibit larger sensitivity to model resolution partly due to the scale-dependent behaviors of physics parameterizations and resolution of surface heterogeneity. Using a variety of metrics, Balaguru et al. (2020) compared tropical cyclones in the DECK LR historical simulation and the HR simulation with observations and showed that tropical cyclones are much more realistic in the HR simulation. More analysis of water cycle processes in the DECK and HR/LR simulations will be reported in the future.

3.2. Biogeochemistry Modeling

E3SM v1 model development for the biogeochemistry driver was motivated by our science question: "What are the effects of nitrogen and phosphorus on climate-biogeochemistry interactions, and how sensitive are these interactions to model structural uncertainty?" To address this question, a major focus has been to add a new capability to model the phosphorus cycle and its interactions with the carbon and nitrogen cycles and evaluating the sensitivity of carbon-climate feedbacks to representations of soil biogeochemistry and nutrient competitions in the land model.

Nutrient availability may limit plant growth and hence the ability of the terrestrial ecosystems to sequester carbon and modulate atmospheric CO_2 concentration and its impacts on climate. Both nitrogen (N) and phosphorus (P) are essential nutrients for the terrestrial ecosystems. Inherited from CESM1, E3SM v0 already includes C and N cycles to represent coupled carbon-nitrogen interactions, so a focus in developing E3SM v1 was to add representations of P cycle to account for coupled CNP interactions and the colimitation of N and P on plant growth. Phosphorous is an important limiting nutrient, particularly in tropical forest ecosystems. Yang et al. (2019) implemented a fully prognostic representation of P cycle and CNP interactions into ELM v1 following the representations of major P pools and fluxes described in Yang et al. (2014). Simulations showed that P cycle dynamics affect both sources and sinks of carbon in the Amazon basin and the effects of P limitation become increasingly important with increases in CO_2 in the future.

To evaluate the structural uncertainty in modeling CNP interactions and nutrient limitation, E3SM v1 features two approaches to modeling nutrient limitation. The two approaches are representative of conceptual modeling based on relative demand (RD) and mechanistic modeling based on ECA. The latter represents nutrient competition between microbes, plants, and abiotic processes. Zhu et al. (2019) benchmarked ELM-ECA against the best knowledge of global plant and soil carbon pools and fluxes and demonstrated robust nutrient constraints on the present-day carbon cycle. Using ELM-ECA, Zhu et al. (2020) further showed that with observationally constrained stoichiometric traits, the model reasonably captured present-day carbon dynamics. They also showed that representing nutrient stoichiometric flexibility in models is necessary to accurately project future terrestrial ecosystem carbon sequestration.

Ricciuto et al. (2018) developed a new method to conduct efficient global parameter sensitivity analysis and applied the method to ELM. They found that less than one third of the 65 ELM parameters examined contributed to the variability of five key land surface variables, including global primary productivity, leaf area index, total vegetation carbon, latent heat flux, and soil organic matter. Further quantification of model uncertainty is important to support the use of Earth system models for informing decisions.





Figure 4. A portrait diagram comparing the global root mean square errors evaluating various coupled model configurations of E3SM v1 against CMIP5 coupled simulations following Gleckler et al. (2008). The fields listed by row are (from top to bottom) 500 hPa geopotential height, 200 and 850 hPa meridional and zonal wind and air temperature, surface air temperature, meridional and zonal surface wind stress, top-of-atmosphere (TOA) longwave and shortwave cloud radiative effect, net longwave and shortwave TOA fluxes, and precipitation. Within each small box, the four triangles separated by the diagonals correspond to winter, spring, summer, and fall seasons clockwise starting from the top. Shown from the left are the two E3SM BGC simulations, followed by the two HR and LR HighResMIP simulations, followed by five ensemble members of the LR DECK historical simulations, followed by a CESM1 simulation. To the right of CESM1 are the coupled simulations from the CMIP5 archive. The BGC and DECK simulations cover 1981-2005, and the HighResMIP simulations cover 30 years after 25 years of model spinup with constant 1950 forcing. Blue (red) means better (worse) than the multimodel ensemble mean.

Using the LR configuration with biogeochemistry turned on, Burrows et al. (2020) provided an overview of the model configurations, simulations, and analysis, focusing on the carbon-climate feedbacks. The biogeochemistry model configuration differs from E3SM v1 used in CMIP6 DECK (Golaz et al., 2019) in several ways: (1) biogeochemistry in the land, ocean, and sea ice components are turned on, although atmospheric CO₂ concentration is prescribed rather than prognostically simulated; (2) two minor bug fixes added after the DECK simulations are included; and (3) the model is retuned to achieve a balanced radiative state. Ocean biogeochemistry is represented using the Biogeochemical Elemental Cycling (BEC) model from CESM1 (Moore et al., 2001, 2004), while sea ice biogeochemistry follows the formulations from the Los Alamos Sea Ice Model (CICE) (Hunke et al., 2015). Biogeochemistry in the terrestrial component uses CTC as the default, with ECA available as an option. This biogeochemistry configuration of E3SM v1 is named E3SM v1.1-BGC and used in all the simulations described in Burrows et al. (2020).

With the default CTC soil biogeochemistry and RD nutrient limitation approach, four coupling scenarios were simulated following the Coupled Climate-Carbon Cycle Model Intercomparison Project (C4MIP) design (Jones et al., 2016). These scenarios facilitate quantification of carbon-concentration (β) and carbon-climate (γ) feedbacks through the indirect physiological pathway (i.e., biogeochemical responses to CO₂ concentration, including fertilization and stomatal responses) and direct radiative pathway (i.e., climate-only effect on carbon), respectively. A subset of simulations using the ECA approach further allows an evaluation of structural uncertainty in modeling the effects of nutrient limitations on β and γ . All scenarios follow the historical pathways for all non-CO₂ forcings for the historical period 1850–2014.

The radiatively coupled simulations of E3SM v1.1-BGC exhibit similar transient behavior to E3SM v1 used in the DECK simulations. Regarding global carbon fluxes, both the CTC and ECA configurations performed better than most individual CMIP5 models. Burrows et al. (2020) reported extensive observational benchmarking of global C, N, and P cycle budgets and analysis of ecosystem responses to

prescribed historical increases in CO₂ and comparison between the CTC and ECA configurations. Based on the differences between the various coupling scenarios, β and γ were estimated over land and ocean. Compared to models lacking carbon-nutrient feedbacks, β estimated by E3SM v1.1-BGC over land is on the low end, and despite significant structural differences between CTC and ECA, the β values converged to 1.0–1.2 PgC ppm⁻¹. Similarly, with carbon-nutrient feedbacks, both CTC and ECA estimated γ values over land on the low end between -5 and -20 PgC K⁻¹ compared to reported values, although the CTC and ECA estimates appear to diverge toward the end of the historical simulations. Also noted was an important distinction between simulations using CTC and ECA—nutrient limitations to the carbon cycle were attributed to nutrient limitation on soil biogeochemistry and plant growth, respectively, potentially leading to larger differences in carbon-climate feedbacks estimated from these models for the future climate.

Figure 4 summarizes the E3SM v1 model skill for the coupled simulations relative to the CMIP5 models using a portrait map. Results shown on the left start with the two LR E3SM v1.1-BGC simulations using CTC and ECA (Burrows et al., 2020), the HR and LR simulations of HighResMIP with constant 1950 forcing (Caldwell et al., 2019), and five ensemble members of the DECK historical simulations at LR (Golaz et al., 2019). To the right of these results are those of CESM1, the predecessor of E3SM v1, and other simulations from the CMIP5 archive. In all configurations, E3SM v1 produced skillful simulations compared to most CMIP5 simulations. With little retuning, the two biogeochemistry simulations have slightly degraded skill compared to the DECK LR simulations. With some retuning, the HR simulation shows overall



improvements relative to the DECK LR simulations as well as its LR counterpart that used the same tuning parameter values of the HR simulation.

4. Concluding Remarks

Developed based on CESM1 in 2014, E3SM v1 includes many innovations in its component models, as documented by the papers in this special collection as well as papers published in other journals. Most notably, E3SM features a unique capability of regional refinement in all of its component models for multiresolution modeling. Compared to its predecessor CESM1 and CAM5 and the last-generation state-of-the-art CMIP5 models, E3SM v1 shows significant improvements in model skill in many aspects of climate simulations. The model was released in April 2018. The E3SM code is available from Github, including scripts and input data for several model configurations documented in the special collection. Information about the project is available from http://e3sm.org, together with information about resources such as documentation of data (e.g., E3SM model outputs for the DECK simulations) and tools (e.g., model diagnostics), and tutorials available to users.

After the v1 release, E3SM became an open development project. Participation in the development and analysis of E3SM has expanded to include more university-based efforts. The E3SM project will continue to advance Earth system modeling through HR modeling on exascale computers and coupled human-Earth system modeling to address science questions related to water cycle, biogeochemistry, and cryosphere systems and energy-mission needs. Development of future versions of E3SM has started in 2018, with parallel efforts focusing on (1) analysis and evaluation of v1 simulations and development of v2 and (2) next-generation development targeted for v3/v4. E3SM v2 will feature new capabilities in coupling natural and human systems and more routine use of regional refinement over North America to more explicitly address DOE's need in understanding Earth system changes affecting the U.S. energy-sector decisions. The next-generation development will invest in science components and software and algorithms for next-generation models to be used in future simulation campaigns. With a close collaboration between the Earth system and computational scientists, the E3SM project represents a unique effort aiming to provide a sustainable path for innovations in Earth system modeling now and in the future.

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Data Availability Statement

The E3SM project, code, simulation configurations, model output, and tools to work with the output are described at the website https://e3sm.org. Instructions on how to get started running E3SM are available at the website https://e3sm.org/model/running-e3sm/e3sm-quick-start. All model codes may be accessed on the GitHub repository (https://github.com/E3SM-Project/E3SM). Model output data are accessible directly on NERSC or through the DOE Earth System Grid Federation (https://esgf-node.llnl.gov/projects/e3sm).

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