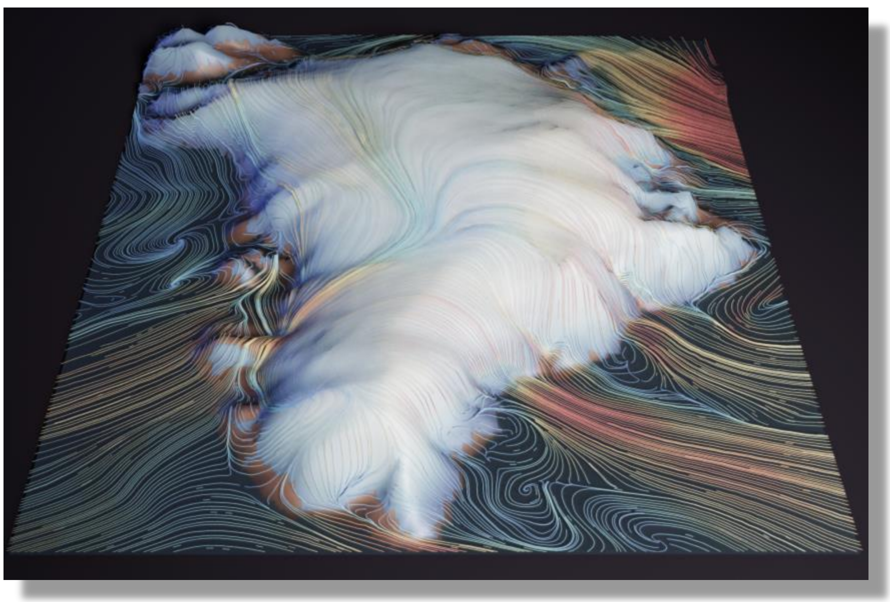
CESM

Community Earth System Model



CESM Science and Strategic Plan: 2023-2028
March 2023

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Cover image: Snapshot of the lowest model level streamlines, draped over the Greenland ice-sheet and colored by wind speed. Simulation was performed with a 1/8° refined grid over Greenland using the variable-resolution configuration of the spectral-element atmospheric dynamical core in CESM2. Katabatic winds can be seen accelerating down the eastern slopes of the ice sheet. Visualization was developed by Matt Rehme (CISL) and Adam Herrington (CGD) of the National Center for Atmospheric Research, and was inspired by a visualization of winds over Antarctica by the Polar Meteorology Group at the Byrd Polar & Climate Research Center.

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Summary

This Science and Strategic Plan provides scientific and modeling priorities and guidelines for the Community Earth System Model (CESM) Project for the next five years. The Plan is based on extensive input received from the CESM community via the CESM Working Groups, starting with the 2019 Annual Workshop, and it is consistent with the vision of both the NCAR Strategic Plan and the Next Generation Earth Systems Science at the National Science Foundation Report. The strategic priorities are determined by the Earth system modeling community's present and anticipated / emerging scientific needs. Our guiding principles include advancing science and understanding of the Earth system and providing actionable information that can be of societal use at relevant temporal and spatial scales in strong collaboration with the community.

The primary niche for the CESM Project is to continue to be the developers of a world-leading, cutting-edge Earth system model at an affordable resolution (order 1°) that is fully documented, supported, and freely available, in collaboration with and in support of the broader climate and university community. This niche builds upon CESM's culture of community involvement as well as a tradition of successes, making CESM the community nexus for Earth system research, both nationally and internationally.

Another priority is to enable research using a hierarchy of models on a range of computing platforms. At one end, CESM will support (ultra) high-resolution configurations. As the ever-increasing impacts of climate change are being felt by society as heat waves, droughts, hurricanes, or sea level rise, just to list a few, decision makers and stakeholders need weather and climate information at the spatial and temporal scales that matter for these events. Such emerging and societally-relevant demands require both much finer spatial resolution than typically used and a step change in our scientific understanding of processes occurring at these scales. At the opposite end of the spectrum, it is also necessary to have CESM versions that are less expensive, more flexible, more user friendly, and faster to run than the standard model versions as part of the CESM hierarchy, strengthening the connections with the university community even more and enabling many applications that require very long simulations and/or targeted idealized experimentation to gain an understanding of processes, mechanisms, and sensitivities.

CESM will play a leadership role in advancing Earth system prediction science on subseasonal to decadal time scales as a priority. This fills a critical niche of providing the community with a system for performing and analyzing initialized predictions of the Earth system as well as serving as a community nexus for prediction research.

Additional priorities include: embracing new emerging developments such as Machine Learning approaches that promise a computationally efficient and scalable means to model the physical, biological, or chemical relationships that can be seen in large observational or high-resolution model datasets; and taking advantage of the rapidly expanding landscape of novel computing architectures and programming methodologies. Finally, effective diagnostic tools are critical to support model development and evaluation as well as

applications of CESM to research questions, and the development of such tools is a continuing priority with increasing emphasis on the use of parallel computing infrastructure for diagnostic analysis of high-resolution datasets.

These priorities will ensure that CESM continues to lead various national and international efforts and assessments to understand and predict the behavior of Earth's climate, positioning and enabling CESM to address emerging, societally-relevant, actionable scientific applications and related challenges.

Introduction

The Community Earth System Model (CESM) is a collaborative, community[1] modeling effort between researchers at the National Center for Atmospheric Research (NCAR), universities, and other national and international research institutions. CESM is used for multiple purposes, including investigations of past and current climate, projections of future climate change, and subseasonal-to-decadal Earth system predictions.

The newest versions of CESM build on many successes of its predecessors. The first global coupled climate model that did not use any flux corrections, which were previously required to stabilize coupled simulations even in the absence of changed radiative forcings, was developed at NCAR. Washington and Meehl (1989) performed several multi-decadal simulations with this model to study climate sensitivity. The first coupled climate model to achieve a stable present-day control simulation without any flux corrections after long multi-century integrations was the Climate System Model (CSM; Boville and Gent 1998). This latter effort was followed by the Community Climate System Model version 2 (CCSM2; Kiehl and Gent 2004), the CCSM3 (Collins et al. 2006), and the CCSM4 (Gent et al. 2011). Additional capabilities such as interactive carbon-nitrogen cycling, global dynamic vegetation and land use change due to anthropogenic activities, a marine biogeochemistry module, a dynamic ice sheet model, and new chemical and physical processes for direct and indirect aerosol effects were added to develop CCSM into an Earth system model. With these new capabilities, the model was renamed the Community Earth System Model (CESM1; Hurrell et al. 2013).

These CCSM and CESM (hereafter just CESM) versions have been at the forefront of national and international efforts and assessments to understand and predict the behavior of Earth's climate, including those of the Intergovernmental Panel on Climate Change (IPCC) and the U.S. Global Change Research Program (USGCRP). Output from numerous simulations using CESM has been routinely used in studies to better understand the processes and mechanisms responsible for climate variability and change. Most of these

[1] The word *community* used throughout this document refers to all entities whose members are engaged in research and / or education in Earth system sciences. They form the collaborative community foundations of CESM. These entities include universities, laboratories, private sector, and other organizations, both nationally and internationally.

studies use CESM's contributions to the various phases of the Coupled Model Intercomparison Project (CMIP). Evaluations of those contributions have identified CESM as among the most realistic climate models in the world based on several metrics that compare the model outputs against present-day observationally-based datasets (Knutti et al. 2013). This tradition continues with the latest model version, CESM2, as its analysis – similarly based on comparisons of a large set of model fields with available observationally-based data – indicates that CESM2 simulations also rank among the most realistic coupled models in the CMIP6 (Eyring et al. 2016) archive with all CESM2 simulations being in the top ten (Fasullo 2020). As a testament to extensive use of various CESM versions by the community, the manuscripts that introduced and described CCSM4 (Gent et al. 2011), CESM1 (Hurrell et al. 2013), and CESM2 (Danabasoglu et al. 2020) have been cited >2700, >1900, and >700 times, respectively, since their publications.

CESM's participation in CMIP6 simulations, including various Model Intercomparison Projects (MIPs), is its most visible and the broadest community project. The datasets from CESM2 CMIP6 simulations are available on the Earth System Grid Federation (ESGF; https://esgf-node.llnl.gov/search/cmip6). Forty-nine manuscripts describing and analyzing these experiments in detail are collected in *the AGU CESM2 Virtual Special Issue* (https://agupubs.onlinelibrary.wiley.com/doi/toc/10.1002/(ISSN)1942-2466.CESM2; also see Danabasoglu and Lamarque 2021). These simulations reach a vast national and international group of researchers who rely on NCAR, and CESM in particular, to perform these simulations. Among the modeling groups which contribute to CMIP6, CESM is very unique in its community involvement and the level of transparency with which it approaches model development. Moreover, many national and international researchers make use of CESM in their research proposals, e.g., submitted to the National Science Foundation (NSF), counting on the CESM's contributions to the CMIPs. Additionally, NCAR and CESM assist the community with the analysis of CMIP simulations by providing a CMIP Analysis Platform (https://www2.cisl.ucar.edu/resources/cmip-analysis-platform) as well as by making many diagnostics tools available for use of the community such as the Climate Variability and Diagnostics Package (CVDP; available at https://www.cesm.ucar.edu/working_groups/CVC/cvdp/; also see Phillips et al. 2014). High level of scrutiny and analysis of the CESM simulations, in turn, feed back to CESM, promoting further model development as well as enhancing collaborations.

CESM has also been used in key activities to advance our understanding of the climate and Earth system and its variability (on time scales up to millennial) and predictability in support of other community driven science efforts. These include the CESM1 Large Ensemble (CESM1-LENS; Kay et al. 2015), the CESM1 Decadal Prediction Large Ensemble (CESM1-DPLE; Yeager et al. 2018), the CESM1 Last Millennium Ensemble (CESM1-LME; Otto-Bliesner et al. 2016), the CESM Stratospheric Aerosol Geoengineering Large Ensemble (GLENS; Tilmes et al. 2018), and the CESM2 Large Ensemble (CESM2-LENS; Rodgers et al. 2021). Additional efforts include all-but-one and single-forcing ensemble simulations to complement full-forcing large ensemble simulations, and participation in various university-led projects, e.g., Climate Process Teams (CPTs) and specialized modeling frameworks. Furthermore, with its interactive dynamic ice sheet models, biogeochemistry, and variable resolution capability, CESM is one of the most comprehensive, cutting-edge models used for paleoclimate studies in the world, e.g., the Transient Climate Evolution of the last 21,000 years (TraCE-21, Liu et al. 2009; iTraCE, He et al. 2021).

Application areas of CESM and its components as well as users of the CESM datasets have been gradually expanding to include stakeholders, policymakers, regional modeling groups, and industry. In particular, interest and demand in simulations with eddy-resolving resolutions in the ocean and tropical-cyclone (TC)- and storm-resolving resolutions in the atmosphere have been steadily increasing to meet the need to provide robust and reliable regional- and local-scale information to society and stakeholders on extreme events, including TCs, atmospheric rivers (ARs), heat waves, winter storms, droughts, floods, and coastal sea-level rise. These demands are consistent with the NCAR Strategic Plan (https://ncar.ucar.edu/who-we-are/strategic-plan) which calls for actionable science to address urgent societal and environmental problems.

This Science and Strategic Plan lays out how the CESM Project – together with the community – intends to prioritize its scientific and modeling efforts during the next five years, in accord with the objectives and recommendations of both the NCAR Strategic Plan and the Next Generation Earth Systems Science at the National Science Foundation Report (National Academies of Sciences, Engineering, and Medicine 2021). Accordingly, following summaries of the Project's mission; vision; management; community and outreach efforts, including diversity, equity, and inclusion; and actionable science and climate justice objectives, the Plan lists several science- and application-driven priorities. These are: ensuring CESM's status as a world-leading, cutting-edge model as its primary niche; enabling research through both (ultra) high-resolution and flexible, lower-cost, and faster, e.g., simple, low-resolution, etc., model configurations; advancing Earth system prediction science; embracing new emerging developments and technologies such as Machine Learning (ML) approaches and the rapidly expanding landscape of novel computing architectures and programming methodologies; and developing effective diagnostic tools that are critical to support model development and evaluation. **It is important to stress that CESM's rather diverse science drivers and goals are articulated within each priority area. They represent a balanced approach to address the needs of the broader CESM community. Also, the Project is always open to getting involved with emerging science questions in response to evolving NCAR and community priorities.** The last part of the Plan is devoted to summaries of component model development plans – including further details of science goals – in support of the listed priorities. This plan is intended to be followed by an Implementation Plan which will include more detailed technical, budgetary, and managerial aspects as well as resource needs and assessments of progress.

CESM Vision and Mission

Vision

To be a world-leading, community Earth system model through pushing the frontiers of state-of-the-science, resolution, and model hierarchy to advance science and understanding of the Earth system and to provide actionable information for societal use in strong collaboration with the Earth system science research and education community.

Mission

- To develop and maintain an open-source, world-leading, cutting-edge Earth system model;
- To perform simulations of the Earth's past, present, and future climates to advance science and understanding of the Earth system and its components;
- To provide useful and actionable predictions of events that impact all members of society at regional and local scales on subseasonal, seasonal, interannual, decadal, centennial, and longer time scales;
- To collaborate with and to provide support to the university community and the broader scientific community – inclusive of under-represented, scientifically marginalized, and climate vulnerable communities – in Earth system modeling, fostering transfer of knowledge.

To accomplish its vision and mission goals, CESM must remain: A national and international leader in Earth system science and modeling; a community hub for advancement and innovation; an enterprise that embraces emerging approaches and technologies; a valued collaborator for the broader community; and a trusted provider of training and mentoring for the current and next generation of Earth system researchers.

Towards these goals, some specific objectives include:

- Enhancing capabilities and application areas of the coupled system, including high-resolution and actionable / societally-relevant applications with human dimension;
- Improving model representations of Earth system processes through incorporation of new components, parameterizations, geotracers, and dynamical cores;
- Using existing and new observations and datasets (including paleo) for: evaluating the model components at process level, quantifying the relative importance of different feedbacks, and obtaining initial states via data assimilation (DA) for Earth system predictions;
- Engaging traditionally under-represented communities in the model co-design and co-development efforts to produce useful and usable information for equitable and just response to climate change;

- Enabling the community to conduct research using a hierarchy of models on a range of computing platforms;
- Providing relevant datasets to the research community;
- Contributing knowledge to national and international assessments; and
- Holding workshops, tutorials, and webinars to foster information exchange and collaborations as well as to train Earth system researchers.

CESM Management

The twelve Working Groups (WGs) form the foundation of the CESM Project (Fig. 1). The WGs are where detailed discussions occur and where work gets done. Their membership is open to any interested researcher who wants to be involved in the Project. Each WG usually has 2-3 cochairs, representing both NCAR and external communities.

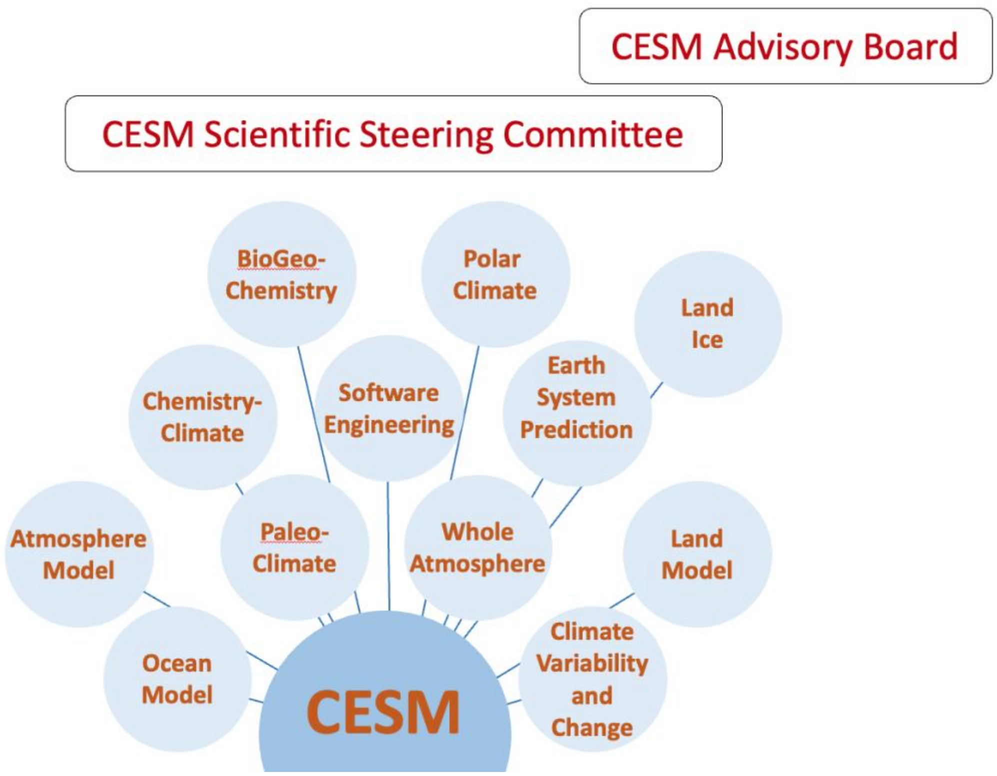

Figure 1. CESM Management.

The CESM Scientific Steering Committee (SSC) provides scientific leadership for the Project, including oversight of activities of WGs; coordination of model experiments; making decisions on model definition and development; and helping with writing of proposals for computer time on the NCAR – Wyoming Supercomputer Center resources and elsewhere. They also lead / contribute to encouragement of external participation in the Project; and promoting CESM.

The CESM Chief Scientist serves as the Chair of the SSC and is responsible with day-to-day operations of the Project. Primary duties include: leading the Project; regularly communicating with the WG cochairs and NCAR and the Climate and Global Dynamics (CGD) Laboratory management; facilitating exchange of information with the WGs and community at weekly-to-biweekly CESM (cochairs) meetings, winter WG meetings, and annual meetings; representing CESM at various national and international venues; advocating for and promoting CESM; and leading writing of various manuscripts, reports, and proposals, including for computational resources.

The CESM Advisory Board (CAB) provides advice to the CESM SSC, the Director of NCAR, the principal sponsors of the project, and the President of the University Corporation for Atmospheric Research (UCAR) on a wide spectrum of scientific and technical activities within or involving CESM. The advice covers the CESM plans, priorities, and management activities, addressing the progress and quality of ongoing CESM scientific and technical activities, their balance, and their interactions with other closely related climate modeling and research projects, with an aim of building a more collaborative modeling community to enhance overall progress in climate modeling. The CAB also promotes the CESM mission, objectives, and activities by helping with building and expanding the CESM national and international community.

Further information on the WGs, CESM SSC, and CAB, including their terms of reference and their current memberships, can be found at https://www.cesm.ucar.edu/management/.

Foundations of CESM

Community and Outreach

Community involvement and community governance (as schematically shown in Fig. 1) are two essential ingredients for CESM's continued success and evolution. They distinguish CESM as the *only* community Earth system model in the world. The community engagement and governance start at the WG level, with at least one external (non-NCAR) cochair for each WG. The current 11-person SSC (regular) membership includes 9 members from the universities and national laboratories. Similarly, the CAB completely consists of members from the university community as well as from both national and international centers and laboratories.

The Science and Software Engineering liaisons for WGs serve a crucial role to enhance communications and collaborations with the community. They also provide help with answering questions and setting up model experiments for university users as well as running community simulations and ensembles. As such, the CESM Project strongly advocates for increased support for each WG to have its full complement of liaisons.

The Annual Workshops and Winter WG Meetings continue to serve as nexuses for information exchange and collaborations with the community, with the last three online Workshops attracting > 700 participants each. The Annual CESM Tutorials as well as shorter tutorials at various national meeting venues continue to educate and train the next generation of Earth system and climate scientists, especially targeting graduate students and early career researchers. Although the CESM Project does not officially track the number of dissertations that use the CESM and its simulations, based on our interactions, the number of applications for tutorials, and requests / questions received from graduate students – both nationally and internationally, we believe that there is indeed a large number of such dissertations – a testament to the reach and value of the CESM Project as a community and educational enterprise. In addition, several CESM-hosted webinar series have become a new mechanism for community engagement and collaboration. Webinar series such as the Modular Ocean Model version 6 (MOM6), Polar Amplification MIP, and Paleoclimate Advances Webinar Series, create a welcoming, inclusive virtual space that facilitate collaboration and broader participation.

CESM, including its component models, is freely available either as releases at www.cesm.ucar.edu/models/current.html or tags on GitHub at https://github.com/ESCOMP/CESM. Similarly, the datasets from CESM simulations are also freely available to the community, following the procedures documented in the *Data Management and Data Distribution Plan for the CESM Project* available at https://www.cesm.ucar.edu/management/docs/cesm-data-management-plan-2021.pdf. CESM takes advantage of a variety of options for distribution of datasets with the primary distribution system being the Climate Data Gateway (CDG). Other means of access to CESM datasets include the UCAR Graphical Information System (GIS) portal; the NCAR Geoscience Data Exchange (GDEX), formerly known as the Digital Asset Services Hub (DASH) Repository; ESGF; repositories at several non-NCAR centers; and cloud-based services.

Diversity, Equity, and Inclusion (DEI)

CESM fosters a diverse, inclusive, equitable, and innovative environment in which all are welcome to contribute towards its vision, mission, and objectives, consistent with UCAR's Diversity, Equity, and Inclusion (DEI) vision as articulated in the UCAR DEI Strategic Plan (December 2019). DEI is a necessary and integral part of our world-leading science and community service efforts. The compositions of the SSC, CAB, and WG cochairs clearly reflect these principals. Indeed, quite a few early and mid-career scientists serve in leadership positions as WG cochairs or SSC members. As stated above and as also detailed below with more specific examples in various sections, the CESM Project embraces open access; community engagement; student involvement; workshops, tutorials, and webinars; and development of tools that make the model and its datasets more accessible and easier to use across multiple platforms. An area that we will pay dedicated attention is more and better engagement of researchers and students from minority serving institutions. We plan to reach out to them individually via in person visits to some of these institutions to explain what CESM does and to learn about their interests, inviting their participation in CESM activities, particularly in the tutorials.

Actionable Science and Climate Justice

Actionable science and climate justice are two related and fundamental objectives (or imperatives) for the CESM Project. In this Plan, we adopt the definition of *actionable science* as given in the NCAR Strategic Plan. Specifically, actionable science "provides sound knowledge, information, or technology that is useful either to the scientific community by supporting research or education, or to society by enabling decision making. Actionable science can be fundamental or applied, and can create benefits over the short or long term." As such, it includes advancing basic science and education. Climate justice is a long-delayed topic not just for the CESM community, but nationally and internationally, particularly concerning racial and societal climate and environment-related justice.

To chart an organized path forward on these two topics in strong collaboration with the community, the 2022 Annual CESM Workshop featured two cross-WG sessions on: i) "Justice and Climate Change", focusing on how scientists can work with communities to produce information for equitable and just response to climate change; and ii) "Actionable Science and CESM", focusing on understanding the nature of actionable science in the context of global climate modeling and the processes and practices for co-developing useful and usable climate science products. The cross-WG discussions indicate that both actionable science and climate justice require progress in the modeling community and the CESM Project, in particular, on i) awareness of how community values and perspectives inform model developments, applications, and evaluations; ii) representation and inclusivity of a wider diversity of values and perspectives in decisions about model development and simulations, i.e., co-development; iii) broader and more comprehensive engagement with traditionally marginalized communities harmed by epistemic (knowledge) and climate injustice and inequity; iv) explicit articulation of, and attention to, the model's inadequacies as they relate to the usability of the model for different actionable and equitable community purposes; and v) easy and equitable access to model, datasets, and computational platforms.

There are already efforts within the CESM community related to actionable science and climate justice. A particular example is related to coastal indigenous communities. Coastal change due to human activities is particularly relevant as warming seas, melting ice, changing weather patterns and disrupted ecosystems converge to affect local communities. Coastal indigenous communities, whose identities and lifeways are deeply connected to these environments, have a wealth of knowledge on past and present conditions and the impacts of changing conditions. Through a new collaborative partnership, indigenous communities across four coastal regions: Alaska, Louisiana, Hawai'i, and Puerto Rico will be working with Earth system scientists and social scientists to co-design research aimed at advancing knowledge on ongoing and future hazards associated with changing coastal weather, coastal inundation and erosion, and marine ecosystems. The project, led by Haskell Foundation, which is connected to Haskell Indian Nations University, will use simulations of CESM, along with process models, downscaled information, and observations, to address questions that reflect local community priorities. This will enable better informed decision making by indigenous communities in these regions regarding possible mitigation and adaptation measures and expand approaches to apply CESM to community scale impacts.

CESM will intentionally broaden its actionable science efforts and actively engage under-represented communities to meet climate justice challenges. We will follow the recommendations that emerged from the cross-WG discussions summarized above. While we recognize that the coarse resolution CESM configurations can be used for societally-relevant science, e.g., changes in extreme events and sea level with a changing climate in projection simulations, there is a growing need for weather and climate information on regional and local spatial scales. The plans for high- and ultra-high resolution CESM efforts to meet these latter demands are articulated below.

A major challenge is that CESM does not have a critical mass of internal expertise to lead and enhance its societally-relevant science and climate justice efforts. Therefore, we will reach out and seek strong collaborations with the leaders, universities, and institutions in the community on these topics to lead and guide CESM's efforts. This approach follows from a recommendation from the CAB that states that CESM's efforts in climate justice should be intentional, well-resourced, and community driven.

The first steps towards entraining and engaging the relevant community may include organizing workshops with under-represented, scientifically marginalized, and climate vulnerable communities and researchers, including those who are already engaged with such communities, to better determine information needs, concerns, and climate problems. Such a workshop would develop an awareness within the broader CESM community of those perspectives that both historically and currently have limited access to climate science tools, datasets, and information. They can also serve as a catalyst to initiate and enhance co-development paths for needed model configurations, datasets, etc. Depending on the outcomes of these efforts, the CESM SSC may consider forming a WG on Actionable Science and Climate Justice or creation of an Advisory Council composed of under-represented communities, stakeholders, and policy makers to provide input to the project.

CESM: A World-Leading, Cutting-Edge Earth System Model

The primary niche for the CESM Project is to continue to develop and maintain a world-leading, cutting-edge Earth system model that is fully documented, supported, and freely available, in collaboration with and in support of the broader climate community. This broad niche builds upon CESM's culture of community involvement as well as a tradition of successes as articulated in the Introduction, making CESM the community nexus for Earth system research, both nationally and internationally. Furthermore, given the world-class reputation of CESM, there is trust in the community that each model version is carefully developed as well as exhaustively and meticulously assessed to produce the best possible Earth system simulation capability. Within this context, CESM serves a very wide audience in support of both curiosity-driven research and larger collaborative projects across various groups. It has a broad range of applications that include research from paleoclimate through space weather with configurations that vary in complexity as a flexible community modeling framework. Through its unique capabilities, CESM can bridge weather, climate, chemistry, and geospace communities.

To keep CESM at the forefront / leading-edge of Earth system modeling and to enable its use in newly emerging scientific challenges and applications require continual evolution of the coupled system and its components. Such efforts include numerical and parameterization developments; addition of new capabilities and of previously missing physics, chemistry, etc.; improved analysis and diagnostics packages; and new configurations with simpler physics and coarser resolutions at one end, and with high complexity physics and higher horizontal and vertical resolutions as well as with regional grid refinement at the other end, just to name a few. Thus, a major thrust of this Plan is the development of a new model version, CESM3, which will contain numerous advancements and new features.

A few specific examples of the ongoing and planned developments and their motivations include:

- Increasing vertical resolution and vertical extent in the workhorse[2] atmospheric model to deliver a unified troposphere-middle atmosphere model with i) a good representation of the stratospheric polar vortices, ii) improved representation of vertical propagating waves that are important for driving stratospheric variability, such as the Quasi-biennial oscillation, and iii) improved representation of profiles of moisture, temperature, and clouds in the boundary layer;
- Incorporating of complete enthalpy fluxes from the atmosphere to the other model components to improve conservation of energy within the coupled system;
- Improving representations of chemistry and aerosols to improve interactions between climate / weather, chemistry, and aerosols, with coupling to the land, ice, and ocean models;
- Increasing the capabilities of the land model to address questions related to ecosystem vulnerability to global change and feedbacks to global change from the terrestrial carbon cycle, and water and food security in the context of climate change, climate variability, and extreme weather;

[2] The term *workhorse* refers to nominal 1° horizontal resolution configurations of the CESM component models or the fully-coupled system routinely used for CMIP-type applications / simulations.

- Incorporating a new ocean model component to better address changes in sea level with a warming climate;
- Improving coupling of the sea-ice with the ocean and simulation of cryosphere-related climate feedbacks;
- Extending CESM's capabilities to simulate dynamic, interactively coupled ice-sheets with a realistic surface mass balance to Antarctica and Laurentide (or paleo) ice sheets to fully enable first-of-a-kind simulations to improve ice-sheet and sea-level projections;
- Enhancing coupling between the biogeochemistry parameterizations in different components of the coupled model to improve exchange of carbon and primary productivity;
- Maintaining and expanding capabilities of the isotope-enabled CESM (iCESM) which may involve incorporation of new ocean geotracers;
- Performing perturbed parameter simulations to reduce parametric uncertainty of carbon cycle processes to improve future projections of carbon uptake by land and ocean systems;
- Expanding DA capabilities, including coupled across components, to facilitate model initialization, parameter and state estimation, and data-driven model development;
- Creating specialized and flexible model configurations that are less computationally expensive for long simulations and developing new infrastructure to make configuring and running CESM easier, for example, using Graphical User Interfaces (GUIs); and
- Democratizing access to the CESM and its datasets via new technologies, such as cloud computing and containers.

The evaluation phase of CESM3 will incorporate simulations of glacial climate and past warm (high CO_2) climates, with comparisons to paleodata, to inform the development of new parameterizations of critical feedback processes. Inclusion of paleoclimate data in the CESM3 development can inform, for example, its climate sensitivity, potential nonlinearities, and tipping points (e.g., Zhu et al. 2020, 2021, 2022). This effort would benefit from enhanced collaborations with the paleoclimatic data community.

CESM3 and CMIP7

We will participate in the next phase of CMIP (CMIP7[3]) using CESM3 configurations as the CESM community sees great scientific value and community service in CESM's participation in these CMIP activities. The primary CMIP simulations, i.e., the so-called Diagnostics, Evaluation, and Characterization of Klima (DECK) experiments, are inseparable from the usual process of developing an Earth system model. The protocols for these experiments as well as those for component-only simulations have emerged as best

[3] The CMIP7 timeline is unknown as of this writing. The CESM Project wishes to follow its own timelines to reduce the stress on personnel and computational resources.

practices over many generations of model development both at NCAR and peer centers around the world. The DECK simulations include an AMIP-style atmosphere-only simulation (Atmospheric Model Intercomparison Project); a long pre-industrial control simulation; an abrupt quadrupling of CO_2 concentration simulation; and a 1% per year CO_2 concentration increase simulation. These simulations will be complemented by ensembles of historical and future scenario experiments to further assess performance of CESM3. It is important to stress that these simulations will be performed as part of our model evaluation process regardless of whether CESM participates in CMIPs or not.

The CESM project fully recognizes the significant strain that broad participation in CMIP efforts puts on limited personnel and computational resources available to the CESM Project. Thus, CESM's engagement in various CMIP7 MIPs will be evaluated and decided by the CESM SSC.

High- and Ultra High-Resolution CESM

As the ever-growing impacts of climate change are being felt by the society as heat waves, droughts, hurricanes, or sea level rise, just to list a few, decision makers and stakeholders need weather and climate information at increasingly finer spatial and temporal scales. Additionally, there are numerous science questions regarding representation of and changes in importance of various processes with increased resolution as well as their interactions with each other – both in comparison with nature and those of coarse resolution (usually order 1° horizontal resolution) simulations as discussed below. It is anticipated that with less reliance on uncertain parameterizations and their parameter choices, the more likely it is that high-resolution models will represent coupled interactions of the Earth system with increased fidelity.

In early 2010s, the CESM Project developed a high-resolution CESM configuration with a horizontal resolution of 0.25° in atmosphere and land and 0.1° in ocean and sea-ice, based on CESM1.3 (Small et al. 2014; Meehl et al. 2019). An unprecedented set of high-resolution simulations[4] have been performed in collaboration with the International Laboratory for High-Resolution Earth System Prediction Project which was terminated in January 2022 (Chang et al. 2020). At these resolutions, the model permits TCs and ocean mesoscale eddies, allowing interactions between these synoptic and mesoscale phenomena with large-scale circulations. In general, high-resolution simulations show significant improvements in representing global mean temperature changes, seasonal cycle of sea surface temperatures (SST) and mixed layer depths, and extreme events such as TCs (Chang et al. 2020). The datasets from these simulations will continue to be analyzed to answer a multitude of science questions that include, for example, changes in ocean heat uptake, ocean upwelling, and modes of climate variability with a changing climate – all in

[4] A 500-year pre-industrial control simulation, a 3-member ensemble of historical and transient (RCP8.5) simulations, an 80-year 1%CO_2 increase simulation, all HighResMIP and AMIP simulations, and a 5-cycle (1958-2018) OMIP simulation.

comparison with the corresponding low-resolution simulations. Additionally, this CESM1.3-based high-resolution configuration[5] will continue to be used to perform new simulations during the life of this Plan, as an alternative to the ultra high-resolution configuration discussed below. Specifically, this configuration provides a platform for the paleo climate community to: study warm and cold climates for process understanding; evaluate extreme weather events, TCs, ARs, and their impacts during past climates; improve climate simulations over ice sheets; and improve model vs. paleodata interpretations near complex topography and ocean upwelling regions. Such studies will have increased benefits if they include a suite of geotracers, such as water isotopes, leading to advancing understanding of extreme phenomena under out-of-sample background climate conditions such as extreme warmth and large continental ice sheets.

During the last decade, primarily driven by actionable and societally-relevant science applications, needs and demands for even higher model resolution simulations increased significantly in the Earth system modeling realm. Such emerging demands represent a Grand Challenge for the climate community, including CESM, requiring both much finer spatial resolution (order 3-10 km) than typically used and a step change in our scientific understanding of processes occurring at these scales. It is an imperative for the CESM Project and its community to answer this call by laying the necessary numerical and physical groundwork for the creation of a coupled model with resolutions that are cloud-permitting in the atmosphere and (sub)mesoscale-resolving / permitting in the ocean. This effort is essential for the CESM community to firmly remain relevant at the forefront of this new ultra high-resolution (~3-5 km) Earth system modeling Grand Challenge.

These high- and ultra high-resolution efforts are well-aligned with the NCAR strategic plan which calls for societally-relevant and actionable science, strategically aligned partnerships with the university community and government agencies, advancement of Earth system science frontiers, support of the community's scientific goals, and development of state-of-the-art community models. As it opens the door to exciting new capabilities and science questions, the effort is complementary to several ongoing activities within CESM, such as NSF-funded CAM7 developments and the CPT efforts as well as work on higher atmospheric vertical resolution.

As alluded to above, the Earth system components interact on a wide range of temporal and spatial scales, involving exchanges of momentum, heat, freshwater, carbon, tracers, etc. at their interfaces. These interactions play fundamental roles in shaping the mean state of the climate system, its variability and change, as well as its predictability and prediction at various time scales, with increasing evidence for importance of small-scale interactions (down to the km scale). Although TC-permitting and mesoscale-eddy-permitting models are becoming more readily available for multi-century climate simulations, including with

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[5] Taking into consideration the input from the WGs, in its 08 July 2020 Meeting, the CESM SSC unanimously recommended that CESM should not develop a new CESM2 high-resolution version, but instead should focus on CESM3 developments with its limited resources and consider creating a (ultra) high-resolution CESM3 version in due course.

the CESM1.3 high-resolution version, at these resolutions moist convective processes and meso- and submeso-scale ocean eddies cannot be fully explicitly resolved, and thus must still be largely parameterized.

In the extratropics, multiscale air-sea interactions are most active in oceanic frontal zones and eddies. In the tropics, such interactions play a particularly important role in a wide range of tropical phenomena, including the Inter-Tropical Convergence Zone (ITCZ), the Madden-Julian Oscillation (MJO), and TCs. Moist convective processes are fundamental to these phenomena and one of the most challenging issues in climate modeling is to accurately represent these processes and their interactions with the large-scale environment and the ocean. Although high-resolution simulations reveal several important improvements resulting from increased resolution, there are aspects of the climate in these simulations that are worse than in the standard resolution simulations. In particular, the rainfall bias along the ITCZ is higher with higher resolution (also see Small et al. 2014). Use of parameterized convection in this class of high-resolution climate models is implicated as a major contributor to these biases.

In contrast, storm-resolving / cloud-permitting models[6] show an impressive agreement between simulated and observed global precipitation and distribution of precipitable water (e.g., Caldwell et al. 2021). These models are based on dynamical cores that solve the nonhydrostatic equations and use global km-scale meshes. As such, they are capable of explicitly simulating deep convection through directly representing clouds by microphysical models, that respond to grid-scale forcing, without the need for a convective parameterization. Simulations with storm-resolving models are also able to produce more realistic MJOs (e.g., Sasaki et al. 2016) and TCs (e.g., Judt et al. 2021), presumably because of their ability to directly simulate the multiscale structure of convective systems and their interactions with the ocean (Satoh et al. 2019). These recent advances demonstrate the importance of explicitly resolving moist convective processes in global climate models. Examples of the many advantages of such configurations are: i) enabling better coupling between cloud, radiation, land-surface, and ocean processes at mesoscales; ii) allowing for multiscale interactions of convective systems from individual deep convection, cloud clusters, and large-scale organized convective systems; iii) permitting circulation-driven microphysical processes by explicitly linking the cloud-scale circulations to cloud microphysical processes; and iv) improving realism of turbulence and gravity wave processes (Satoh et al. 2019). The potential to improve these processes and subsequently lessen systematic biases via cloud-permitting resolutions will therefore have large implications for the broader CESM community.

An impediment towards an ultra high-resolution CESM is the lack of non-hydrostatic (NH) capabilities within the Spectral Element (SE) dynamical core (dycore) of the Community Atmosphere Model (CAM) with which the CESM atmospheric model developers are most familiar. To expedite progress, we plan to utilize the Department of Energy (DOE) Energy

[6] Such as those participating in the DYnamics of the Atmospheric general circulation Modeled On Non-hydrostatic Domains (DYAMOND) project.

Exascale Earth System Model (E3SM)'s version of the CAM SE-NH version (Taylor et al. 2020; Caldwell et al. 2021) which has been developed for both Fortran and C++ software – both available on GitHub. The availability of the Fortran version means that once the implementation is completed, CESM can take immediate advantage of the SE-NH version. The C++ version has already been optimized for the newest computer hardware generations with support for Graphics Processor Units (GPUs). This ensures that the integration of the NH capabilities is fully consistent with the changes in the high-performance computing landscape. Because this SE-NH configuration will primarily be relevant for high- to very high-resolution climate assessments, either using locally-refined variable-resolution or globally-refined grids, the acceleration on GPUs is a paramount step towards reasonable integration rates. It is expected that SE-NH will be able to take full advantage of the GPU portion of the new NCAR Supercomputer Derecho, providing new opportunities for CESM and the community. With this approach to incorporation of the SE-NH capability, CESM benefits from the extensive software engineering development done by the E3SM team, and reinforce the longstanding DOE-NSF collaboration. The E3SM and overall DOE leadership are extremely supportive of this approach.

As indicated above, one of the main reasons for using the SE dycore for this effort is because the primary CAM developers have extensive experience with this dycore in climate applications. We think that such experience is important to address any emerging challenges on the way. Furthermore, SE-NH represents an intermediate step in complexity from the current SE hydrostatic core's pressure-coordinate to the altitude-coordinate non-hydrostatic Model for Prediction Across Scales (MPAS). Several parameterizations and the CAM physics static energy formulation were developed with constant pressure assumptions; and achieving total energy conservation and thermodynamic consistency – both important properties to preserve for long, climate-scale simulations – in CAM physics with a height-based vertical coordinate is not straightforward. Therefore, any existing developments would only incrementally increase the complexity of the modeling approach by keeping the vertical coordinate as pressure, thereby not impacting the current use of the CAM version 6 (CAM6) physics suite. Another important point is that the SE-NH capability will be implemented as an extension of the current SE dycore – not as a separate dycore, requiring no changes to the current implementation of the SE dycore and its associated tools and infrastructure within the System for Integrated Modeling of the Atmosphere (SIMA), guaranteeing a smooth transition and offering enhanced scientific capabilities for community members. Additionally, having capabilities with both SE and MPAS dycores makes CESM (and NCAR) better prepared for future architectures, collaborations with other modeling centers and groups, and numerical methods research. Moreover, two dycores that can support GPU applications present a unique and advantageous position for CESM: one weather-focused (MPAS) and one more climate-focused (SE-NH), with both under the same SIMA framework. As the path to exascale computing right now is rather complicated and not settled at all (see below), CESM will likely have to live with multiple approaches for quite some time, providing us valuable experience and help build capacity. For example, leveraging synergies and collaborating with the NSF-supported EarthWorks Project that uses MPAS will advance both CESM and the EarthWorks.

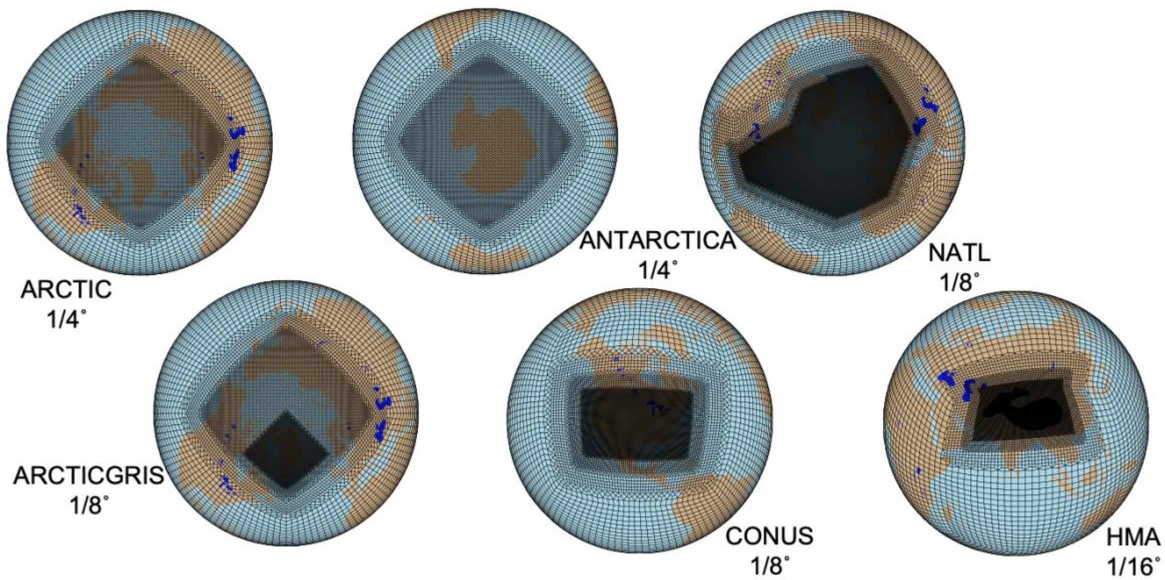

Figure 2. Samples of SE regionally-refined grids.

Another important consideration is that SE's variable-resolution / regional-refinement capability (Herrington et al. 2022) serves as a bridging technology for the community which allows cloud-permitting studies in limited domains at affordable computational costs. Several such configurations have been already in use for various scientific applications (Fig. 2). They include simulations with: the North Atlantic regionally-refined configuration to address deficiencies in jet stream variability in relation to North Atlantic SST variability; the Arctic regionally-refined configuration to study surface mass balance over Greenland with increasing CO_2; and regionally-refined configurations over South Asia to study air quality and Asian summer monsoons. As these configurations target increasingly finer refinements, they push the boundaries of the hydrostatic assumption. Thus, an immediate application area of SE-NH capability will be in these regionally-refined configurations.

Indeed, an initial scientific application will use grid refinement over the continental US, i.e., the CONUS grid, with a fine grid of ~3 km to study mesoscale convective systems in short simulations. A second application will consider air-sea interactions, tropical precipitation, and TCs in both AMIP-style and coupled 40-day simulations following the DYAMOND protocol with target global resolutions of ~3 km. The ocean and sea-ice components will use ~0.1° resolution as we have extensive experience at this resolution. As we gain more experience and subject to availability of resources, we may consider higher ocean and sea-ice resolutions and / or longer simulations. Another path is to use embedding approaches in certain ocean regions to match the regionally-refined grids used for the atmosphere.

Of course, there are many challenges that need to be addressed in this ultra high-resolution endeavor, such as a need for scale-aware parameterizations and adequacy of existing parameterizations at such high resolutions. Relatedly, these configurations are very costly to tune, and long coupled simulations, even for multidecadal timescales, are not possible with traditional parameterizations and computational frameworks. For CESM to go beyond the short timescale science applications discussed above, it must develop a balanced strategy for tuning and efficient running of these configurations for long (decadal or longer) simulations, taking advantage of ML techniques and GPU approaches discussed below.

Specialized and Flexible CESM Configurations

A key strength of CESM is its support and flexibility for specialized configurations that are often necessary and better positioned to isolate complexities of the Earth system and answer a wide range of fundamental questions in climate dynamics. Such configurations include simpler simulations with reduced physics and chemistry (e.g., single column, aquaplanet, coarser-resolution, and slab-ocean configurations) – that are much less computationally expensive so that they can be run at academic settings – and specialized simulations of paleoclimate and planetary atmospheres that use boundary conditions that are very different from today's. Another major use area for these configurations is applications that require long simulations, such as multi-millennial-long paleoclimate experiments, conducted to tackle glacial-interglacial climate change with an interactive ice sheet model with a model throughput of >100 simulation years per wall-clock day. Many CESM users, especially at universities, wish to use CESM in these specialized and flexible configurations to isolate complexity and test new hypotheses. The continuous support of these configurations provides a CESM model hierarchy for bridging the gap between theoretical understanding and the real Earth, further strengthening the connections with the university community. Additionally, sufficient guidance must be provided to the community on which versions and configurations are useful for which applications.

CESM will continue to develop tools and infrastructure: to allow users to easily determine the available configurations in the model hierarchy and their characteristics; to easily modify initial conditions, boundary conditions, input datasets, biogeophysics modules; and to easily reconfigure the continents, orography, and bathymetry for paleoclimate and exoplanet research applications. Enhanced flexibility in available configurations means having a variable complexity in model components, such as including a simplified land model, a dynamic vegetation model untethered to modern vegetation, prescribed aerosols, simpler chemistry, or a reduced-complexity ocean biogeochemistry model. CESM will continue to develop a GUI-based tool to configure the model with ease. A gold standard in these model efforts is that CESM must be easy enough to use and configure so that a graduate student can easily set up and run simulations. CESM will develop and maintain a website to communicate specialized and flexible modeling efforts that can contain links to FAQs and available configurations on GitHub. The site can also collect contributed recipes that can come from the community to set up non-standard CESM configurations.

Earth System Prediction

Interest in Earth System Prediction (ESP) on time scales from subseasonal to decadal has grown rapidly within both the national and international climate research communities during the last decade. Several factors have contributed to such a rapid growth in this research activity, including: i) the growth in computational resources that now permit routine large ensemble simulations needed for prediction experiments; ii) the refinement of techniques for merging observations and models, allowing for state reconstructions that go back decades and extend into the present; iii) the publication of groundbreaking ESP studies that have demonstrated considerable promise of skillful predictions; and iv) the steady increase in societal demand for reliable near-term climate information. The enormous social, economic, and environmental impacts associated with future changes in the Earth system can best be anticipated using initialized predictions. Such predictions of the near-term evolution of the Earth system to provide societally-relevant, actionable information are one of the main goals of the NCAR Strategic Plan. Indeed, it advocates for "expand[ing] capabilities for assessing and predicting societally relevant climate variability and change on time scales ranging from seasonal to interannual to centennial", and it calls for "enhancing the flexibility of modeling system to enable integration with observations and initialized Earth system prediction for the purpose of investigating model physics and biases, bridging weather and climate, and understanding evolution toward future climate states."

CESM will play a leadership role in advancing ESP science to fulfill its mission of science in service to society, consistent with the NCAR Strategic Plan. In this role, CESM fills a critical niche of providing the community a system for performing and analyzing initialized predictions of the Earth system as well as serving as a community nexus for ESP research. Scattered and piecemeal ESP efforts by individual university researchers would be duplicative and would be unlikely to match the level of quality, comprehensiveness, synergy, and coordination that could be achieved through CESM's (and NCAR's) leadership and service to the community.

Over the next five years, CESM will focus on leading and facilitating community efforts to understand the sources of predictability on timescales from subseasonal to decadal, and exploring the many uncertainties and unknowns associated with ESP system design, such as: land, ocean, atmosphere initialization; ensemble spread; limits of predictability; drift; and bias correction. An important focus area is ESP with a high-resolution (0.25° atmosphere and land, and 0.1° ocean and sea-ice) CESM configuration to address questions about the role of horizontal resolution on predictability and prediction skill and to provide refined and regional-scale prediction information that can have more societal value. Indeed, initial results from a limited set of high-resolution decadal prediction simulations with CESM1 show that overall skill and signal-to-noise properties of several fields of interest are significantly enhanced with increased resolution compared to those from lower resolution simulations, suggesting an important role for mesoscale ocean – atmosphere interactions in improving prediction skill and signals (Yeager et al. 2023). Another focus area is a CESM configuration with a well-resolved stratosphere to examine stratospheric influences on prediction, possibly merging the subseasonal prediction system with an existing air quality system. These efforts build on subseasonal ESP simulations with CESM2 using both the low- and high-top atmospheric model versions (Richter et al. 2022), Seasonal-to-MultiYear Large Ensemble prediction simulations with CESM2 (SMYLE; Yeager et al. 2022), and CESM1 Decadal Prediction Large Ensemble (CESM1-DPLE; Yeager et al. 2018) that show that CESM has impressive prediction skill at various time scales for many fields of interest, e.g., land surface temperatures, regional precipitation, and Nino3.4, that are comparable to or better than those of other prediction systems. Datasets from these simulations are also being used for prediction of fish habitat and distribution shifts (Payne et al. 2022) and exploration of mesosphere and lower-thermosphere predictability (Pedatella et al. 2021).

ESP is still a rather new field, especially on interannual and decadal time scales. As such, there are numerous scientific and technical challenges that are common across time scales and across research and operational efforts. Although CESM does not seek to provide operational forecasts currently, the fundamental ESP research undertaken by CESM will undoubtedly help the operational community. For example, using CESM2 subseasonal simulations, Davis et al (2022) elucidated the stratosphere's role in cold air outbreaks in Northern Europe and demonstrated that the stratosphere did not play a substantial role in the severe outbreak of 2021. Such fundamental research is clearly very valuable. Along these lines, key science questions that can be addressed by CESM include: how and at what time scales do individual Earth system states (land, atmosphere, ocean) or phenomena (volcanic eruptions) affect predictability and how does system design impact prediction skill? The latter includes impacts of resolution, stochastic physics, and different initialization methods, such as (coupled) DA, reanalysis, etc. Another high-priority science objective is to determine how CESM model development can be informed by initialized prediction work, which allows one to confront the coupled model directly against observations in a way that other experimental frameworks do not permit. In all these efforts, development of diagnostics and analysis tools tailored to the needs of the ESP research, such as, ensemble analysis, skill metrics, drift-correction methods, and highly parallelizable workflows, as well as support for university partners and coordinated community collaboration on science questions and diagnostics development are crucial.

Pursuing New Technologies to Advance Science

Machine Learning with CESM

As discussed above, CESM scientists would like to be able to run models at finer resolutions with more processes represented and coupled together to improve the realism of the simulations, but these scientific ambitions are challenged by the expected trajectory of our computing resources. ML approaches promise a computationally efficient and scalable means to model the physical, biological, or chemical relationships that can be seen in large observational or high-resolution model datasets. The use of CESM data for training ML models for process-understanding, predictability, parameter estimation, and model improvement studies is an exciting scientific research path – articulated below – in its infancy. In response to this potential, the extent and diversity of the application of ML to CESM research have grown significantly in the past few years in collaboration with university and industry partners, all in line with the rapid increase in interest across the Earth system science community. This increase in activity culminated with a cross-WG session on ML in CESM at the 2021 CESM Annual Workshop and the initiation of an ML in CESM page on the CESM bulletin boards.

ML opens interesting opportunities for physical parameterization development in all CESM component models. In general, Earth system model simulation uncertainties are dominated by model errors, which can be traced to deficiencies in the representation of key physical and biological processes, either because these processes occur at scales too small to be explicitly resolved on the coarse (~100 km) spatial grid of the model (e.g., clouds), or because basic understanding is limited (e.g., land biology/ecology). In recent years, we have witnessed a dramatic increase in the availability of large or unique datasets that can be utilized to better constrain or parameterize these uncertain processes, including high-resolution process-resolving simulations, and observations from new and existing satellite observing systems as well as new in situ data.

ML algorithms are data-hungry, requiring many more samples to learn their many free parameters. Because of this, CESM simulations, including large ensembles, long control and high-resolution runs, provide a vast amount of data with which to train ML models. These ML models may be designed to gain insight into the physical processes simulated within CESM and / or to evaluate CESM's ability to simulate observed processes. Furthermore, ML post-processing of CESM hindcasts across lead times, e.g., Earth system predictions at various time scales, can potentially bias correct forecasts for improved performance, and provide insights into sources of climate predictability.

Over the past few years, several proof-of-concept ML parameterization projects have been conducted for various CESM components. For example, the CAM parameterization for warm rain formation was replaced with an emulator derived from a high-resolution cloud resolving simulation. When implemented, standard resolution CAM can reproduce warm rain formation features seen in the cloud-resolving model but that are not captured in default CAM. Additional emulator projects have focused on modeling the atmospheric boundary layer, simulating the atmospheric chemical reactions of volatile organic compounds, and optimizing the parameters of land surface models. A team of atmospheric chemists and computational experts has developed emulators for the GECKO-A chemistry box model and successfully produced accurate time series predictions of the evolution of hydrocarbon precursors into gas and aerosol products. ML emulators of the Community Land Model (CLM) have enabled the evaluation and estimation of multiple model parameters to determine optimal joint distributions of parameter values for the global land model.

Another promising ML foundational activity is a collaboration with engineers from the Climate Change Canada and the Artificial Intelligence and Advanced Productivity division at Hewlett Packard Enterprises (HPE). This effort uses HPE's SmartSim library, which enables online analysis and ML for traditional high performance computing simulations by linking compiled language codebases (C, C++, Fortran) to rapidly evolving ML and data analytics libraries that are typically written in Python. SmartSim uses an in-memory database to eliminate dependence on file input and output which allows most ML and data analytics packages to be used at the scale needed for global climate simulations. The team has successfully hooked SmartSim directly inside of standalone MOM6 – the new CESM ocean component, and in preparation for using it throughout the rest of CESM has also instantiated SmartSim within the Common Infrastructure for Modeling the Earth (CIME). The capabilities of SmartSim have been demonstrated by utilizing output from an eddy-permitting (0.1°) MOM6 global ocean simulation to extract training data for a neural network to predict oceanic eddy kinetic energy (EKE). The neural network was invoked in a prognostic 0.25° simulation to replace the existing EKE parameterization. The inferred values of the EKE were then fed into the calculation of the Gent and McWilliams (1990) mesoscale mixing parameterization coefficient.

Over the next several years, the CESM project intends to explore and integrate the use of ML methods into CESM parameterization and parameter estimation activities as well as model analysis through collaborations on several large projects (see below) and other PI-driven projects. These will emphasize advanced scale- and physics-aware deep learning algorithms, probabilistic deep learning algorithms, and interpretable ML-based toolkits for physics discovery, and will also aim to overcome challenges related to ML for Earth system modeling that include sampling efficiency, generalization, interpretability, and uncertainty quantification. The incorporation of any new ML-based parameterizations or modifications in CESM will follow the established protocols that includes consideration of performance under different climates within the coupled system, tangible model improvements, as well as thorough understanding of undelaying physics, chemistry, etc.

Multiscale Machine Learning in Coupled Earth System Modeling (M²LInES)

The M²LInES project, sponsored by the Schmidt Futures, will develop new ML-based parameterizations to capture unaccounted physical processes that affect the air – sea – ice interface. This work involves analysis of high-resolution simulations and observations with scientific and interpretable ML to gain insight into and better simulate unresolved processes. Atmospheric parameterizations that are under consideration are boundary layer processes and atmospheric convection and clouds. For the ocean, vertical mixing, mesoscale buoyancy fluxes, submesoscale processes, and mesoscale momentum, energy, and air-sea interactions are being addressed. Additional work is underway to characterize sea ice heterogeneity and its influence on air – sea ice fluxes. Furthermore, mismatches between a traditional physically-based parameterization and observations (structural uncertainty) can be learned with ML as a state-dependent bias correction which can then be used to correct the model structural errors. These efforts are in varying states of readiness for inclusion in CESM with some candidate parameterizations for the ocean and atmosphere already developed. For example, two ocean parameterizations – a planetary boundary layer scheme with a neural network based vertical eddy diffusivity and a neural network backscatter scheme (Zhang et al. 2023) – learned from high-resolution simulations have been incorporated into MOM6 already, and they will soon be tested in CESM.

The Center for Learning the Earth with Artificial Intelligence and Physics (LEAP)

Leap is a new NSF-funded Science and Technology Center, hosted at the Columbia University, that includes partnerships with CESM, other universities, and industry such as Google. LEAP focuses on reducing errors in near-future climate projections by replacing subcomponents of Earth system models with novel ML algorithms that are able to better extrapolate by including domain knowledge and aggressively leveraging the wealth of information in recent high-resolution model and observational datasets. Different ML methods will be employed for data rich, data moderate, and data poor situations. Specifically, LEAP will focus on: i) reducing existing model structural errors related to the lack of understanding of the processes at play, e.g., clouds and microphysics; ii) optimally estimating model parameters using a Bayesian approach; and iii) developing new observational products from sparse data from ML methods which will be used to evaluate the CESM skill.

Model representation of key physical processes, e.g., clouds, convection, will require new families of parameterizations that better approximate the underlying physics. To improve climate simulations and projections, LEAP will define a new generation of ML-based parameterizations while imposing physical constraints throughout the algorithm development. Illustrative project examples include:

<u>Learning Parameterization Models from Observations or High-Resolution Model:</u> Direct ML, e.g., for atmospheric convection and ocean eddies, or equation discovery can learn parameterized processes directly from observational data or coarse-grained high-resolution simulations. Parameterizations can be deterministic or stochastic, e.g., noise can be time- and state-dependent.

<u>Learning Parameterization Models from High-Resolution Model and Correcting It:</u> The strategy developed above using high-resolution, process-resolving models can still exhibit biases. For instance, even a high-resolution cloud resolving model at ~1 km resolution can be prone to biases, e.g., top of the atmosphere energy imbalance, fundamentally limiting its use for climate projections. LEAP will correct this model using various strategies informed by observations – using transfer learning to adjust the knowledge from the high-resolution model to the observations or using a post-processing correction using ML.

<u>Emulating Parameters:</u> Underlying physical- or ML-based model parameters can be optimally estimated using ML emulators and a Bayesian approach to estimate the posterior distribution of the parameters.

Overcoming Technical Challenges Associated with (Ultra) High-Resolution Science Efforts

The push to be on the cutting edge of extremely high-resolution modeling with CESM is exciting, but also brings with it numerous technical and logistical challenges. At a fundamental level, it will require significant efforts in software engineering focused on *technical* aspects of infrastructure, performance, and scalability. By the nature of its mission, the CESM software engineers focus their efforts on *science* aspects of the model via new, sophisticated physics, ease of use, portability, correctness, and community support. It is important to strike the right balance between these competing technology-focused and science-focused design approaches, and achieving this will require improved, open planning and coordination both within CESM / NCAR and with our external user community and collaborators.

One early and critical aspect of this coordination will be to continue to engage with the NCAR's Computational and Information System Laboratory's (CISL) Technology Development Division (TDD) on the creation of a forum on the *codesign* of advanced modeling capabilities for CESM. This collaborative effort, already underway, will leverage unique skills and insights from experts in both CGD and CISL to address the most complex technical challenges within CESM, and help further NCAR's mission and its Strategic Plan as a whole.

At the same time, CESM is already pursuing solutions to several technical issues relating to high resolution, with more on the horizon. Recent experiences launching global 7.5 km and 3.75 km meshes highlighted issues with memory scalability within CAM and Earth System Modeling Framework (ESMF) when taking these components into tens of thousands of cores. Although these issues were addressed quickly, it is expected that similar issues will be found with the other components as we push to new ultra high resolutions for the entire Earth system model.

As CESM is scaled up, data storage and I/O become critical issues requiring significant attention – work is already scheduled for including asynchronous capability to Parallel I/O, the underlying I/O framework that is used by both CESM and SIMA. This new capability will not only improve performance for the massive increases in data associated with high resolution, but also enable additional future enhancements such as runtime compression of output, which is nearly essential at these scales – see software engineering plans below for details on compression. More novel techniques such as in-situ diagnostics are also being actively discussed, and the planned codesign forum will look at new hardware capabilities for faster I/O as well.

Even seemingly 'simple' problems such as model logging will need to be refactored in the exascale regime; finding an error message when running on hundreds of processors is doable, but the problem becomes much more difficult when on tens of thousands or more. Fault tolerance and recovery in the event of hardware failure will also need to be addressed. This is something that is marginal on hundreds of cores, but essential when running several orders of magnitude above that. Finally, load balancing becomes more critical, as computations are generally rate-limited by the process with the most work, and any imbalance can be magnified greatly by massive process counts.

Looking further ahead, two of the newer developments in computing technology are the advent of sophisticated ML models (as discussed above) and the rapidly expanding landscape of novel computing architectures, or 'accelerators', like GPUs. Regarding ML, better coordination between the ML projects, CESM, and CISL should lead to new approaches that offer improvements in performance or scientific accuracy, or both. On the accelerator front, we are looking at multiple strategies, including directive-based methods like OpenMP and OpenACC and Domain Specific Languages (DSLs) like GT4py and PSyclone. Modern GPUs have the potential to greatly improve the energy efficiency of our supercomputer, but also require significant investments in software engineering to take advantage of and, without additional funding, these efforts will inevitably come at the expense of science-focused software engineering goals. Understanding where these trade-offs are worth it, both to NCAR and to the wider CESM community, will be an ongoing, shifting conversation as needs and hardware alike both evolve.

In summary, CESM is already prioritizing the ability to run the fully coupled model configuration at extremely high-resolution capability. A partnership with CISL and the broader community in this area will help ensure the success of the effort to create portable, performant programming methodologies on both current and future computing platforms. Success in this plan will require continued prioritization of CESM technology leadership along with a strong focus on broad communication efforts both across NCAR and within the CESM user community, including private sector partners.

Diagnostics

Effective diagnostic[7] tools are critical to support model development and evaluation as well as applications of CESM to research questions. Historically, individual CESM WGs have built diagnostic packages largely independently of each other. These packages have served a valuable purpose; however, they have reached end-of-life, as they are based on deprecated languages (e.g., NCAR Command Language, NCL) and are increasingly fragile and difficult to deploy or extend. Simultaneously, new technologies have emerged in the context of open-source data science software, ML techniques, and cloud computing platforms; these dramatically expand the realm of possibilities for our conception of model diagnostics.

We envision a future where the effort to build analytic workflows with model data, including diagnostics, is a fundamental priority for the CESM development community. Through the effort to build model diagnostics, we seek to develop an interactive numerical laboratory for Earth system science, easily deployed on high performance computing and cloud platforms. As a foremost requirement, this framework must provide an efficient means of evaluating model performance through intercomparison across model solutions or skill assessments relative to observations. However, we ultimately aspire to a broader vision for diagnostics: democratizing access to model results, thereby accelerating applications of CESM to creative cutting-edge research, actionable science, or decision support frameworks. The approach to the design and development of model diagnostics

[7] The term “diagnostics” refers to tools that are used in model evaluation and analysis through either visualizations or statistical summaries, usually in comparison with available observations, reanalysis products, or other model solutions.

will proceed with this broader strategic goal in mind. Requirements in this context include a framework that is performant and portable across multiple platforms. Diagnostic packages must generate outputs (i.e., visualizations, products of analysis) that are accessible via easily navigable web-based portals. The diagnostics packages should explicitly support extensibility to make adding new outputs easy. The packages should be wholly modular, and support configurability and the generation of bespoke combinations of analysis elements and output suites. Critically, a design that fulfills these requirements can effectively be used as a launch point for ad hoc extensions, thereby supporting seamless integration of routine model evaluation with analysis workflows supporting cutting-edge research. An ability to rapidly configure *dashboards* targeting particular dynamics or topical concerns (e.g., tuning metrics) will accelerate the model development cycle and set the stage for broadening access to results beyond expert researchers. Finally, although file-based post-processing will remain a primary diagnostic paradigm, CESM will develop a *diagnostic component* to provide an avenue for implementing diagnostic calculations online while the model is running. Realization of this vision will consider the following guiding principles.

Scientific Python

CESM diagnostics will predominantly use Python, which provides exceptional capabilities for constructing performant analysis and visualization workflows. Notably, scientific Python comprises an ecosystem of tools, organized into interoperable packages, each with a particular functional scope. CESM diagnostics must embrace this development paradigm, leveraging package-management tools to construct comprehensive functionality through collections of compatible packages. Xarray is an important package to identify specifically. It invokes a netCDF-like data model, providing data structures with dimensions, coordinates, and attributes. Xarray integrates with Dask – an open-source library for parallel computing written in Python, which provides opportunities for parallelism and distributed computation in high performance computing and cloud environments. CESM analysis codes should be based on the Xarray data model, with operators that consume and produce Xarray datasets. CESM analysis codes should also specifically seek to leverage Geoscience Community Analysis Toolkit (GeoCAT[8]), which implements tools for geoscientific analysis.

Community-oriented development

The effort to develop CESM diagnostics will be community-oriented, seeking to leverage contributions across a broad network. Notably, the core infrastructure will depend on engagement with the Pangeo community, which has provided both inspiring technical solutions to Big Data geoscience problems and paradigms for large-scale community collaboration. Additional resources and communities include large-scale efforts at the National Oceanic and Atmospheric Administration (NOAA), such as the Model Diagnostics Task Force, and international efforts, such as ESMValTool. Ideally, the CESM diagnostics framework would leverage functionality in these complementary efforts, while

[8] GeoCAT development is coordinated by CISL.

also retaining a perspective focused on supporting both routine model validation and flexibility enabling ad hoc analysis workflows.

Modular workflows

Model diagnostic workflows involve reading data, performing some computations, constructing visualizations, and finally providing structured access to the diagnostic output via a web page. It is critical to design and implement packages that provide general solutions for the common components of this diagnostic workflow. This will enable modularity, extensibility, and a core infrastructure that is shared across components and WGs. Moreover, through a modular design, significant computational elements of the diagnostics tool chain remain accessible for use in ad hoc analysis workflows outside the diagnostics framework. Ongoing efforts have produced a preliminary design concept in this context, identifying several key components:

<u>Data catalog:</u> Abstraction that hides file system details, provides parameterizable access to data assets, supports portability across computing platforms, and stores information enabling operations to change behavior contingent on metadata. Data catalogs can also support search and discovery operations.

<u>Workflow management system:</u> Automate application of analysis *recipes*, which might include common computations, such as dimension reduction operations.

<u>Analysis operators:</u> Algorithms that consume and produce Xarray datasets, supporting the computations necessary to generate diagnostic output; rely on GeoCAT and the broader scientific Python stack for key functionality.

<u>Dashboard viewers:</u> A generic solution to visualizing collections of diagnostic plots, enabling construction of configurable dashboard interfaces from arbitrary collections of plots. This approach alleviates tight coupling between analysis code and the visualization framework, providing an Application Programming Interface (API) that makes changing one without the other easy.

<u>Jupyter Notebooks:</u> Jupyter Notebooks provide an interactive computing environment, mingling code, visualizations, and documentation. Furthermore, Jupyter Notebooks are increasingly capable of supporting interactive visualizations and compilation into sophisticated web pages. Building model diagnostics as collections of parameterizable notebooks that can be run in batch mode and subsequently compiled into a web page can provide several advantages.

Online analysis

Motivation to explore online diagnostics include limitations to data storage, particularly at high-resolution or for long, multi-millennial integrations, as well as potential for new capabilities arising from an ability to operate on state information as the model is running. A general approach to supporting online diagnostic computation would be via a diagnostics component, which would interface with the coupled system like other component models and provide hooks through which to couple analysis codes, including those written in Python.

Machine learning

Recent developments in model calibration, parameterization, and post-processing have demonstrated that ML can offer advantages over more traditional analysis paradigms. Future CESM diagnostic workflows are likely to invoke ML algorithms and must include support for utilizing ML software packages, leveraging computing resources such as GPUs, and constructing efficient ML pipelines, including necessary data reformatting steps.

Platforms and formats

Cloud computing has emerged as an effective alternative for analysis workflows. Seamless public access is a significant advantage of putting data in the cloud; this, coupled with effective analysis environments, offers opportunities to democratize access to model results. Cloud-based analysis platforms will rely on JupyterHub deployments, which should support multiple cloud-vendors and be easy to configure. This will require effective partnerships with CISL, other NCAR laboratories, and possibly entities such as 2i2c.org. In general, the CESM project should adopt a *cloud forward* perspective, seeking to identify opportunities to build cloud-based workflows and deployments[9]. Critically, analysis workflows should aim to support both cloud and high-performance computing platforms, which has implications for data access mechanisms and storage formats. An effective data cataloging framework can support different file formats or data configurations (i.e., time series versus history files) in a manner that is opaque to the user from a syntax perspective. Different file formats and configurations can have significant performance implications for analysis I/O and these characteristics vary across computing platforms. Identifying optimal formats in which to store model output on various platforms is a requirement.

Model and Infrastructure Developments

To accomplish the science, and model and technical improvement goals and objectives discussed above and to keep CESM at the forefront of Earth system modeling in the world require continual evolution of the coupled system, its components, and its infrastructure. In this section, summaries of planned developments for each component are provided along with their scientific justifications that are guided by the science framework presented above. Majority of these developments are targeted to be completed during the first half of this Plan’s duration and will be available to the community as a new model version, CESM3.

[9] A community-wide strategy needs to be developed to address financial challenges associated with the use of cloud-based infrastructures, e.g., paying for downloads.

Atmosphere Model

The Atmosphere Model Working Group (AMWG) guides and supports the development of CAM and associated capabilities. This encompasses work to improve the representation of unresolved physical processes in the atmosphere, i.e., parameterizations, work on algorithms to explicitly simulate dynamical processes including tracer transports, as well as work to understand how these processes manifest themselves in the Earth system at a range of temporal and spatial scales. AMWG is also tasked with ensuring that CAM can be configured to satisfy the needs of a broad cross-section of the research community. Unlike any other component of CESM, the atmosphere couples to all other components. Thus, AMWG works closely with all other CESM WGs to ensure that the crucial atmospheric coupling is accurate as well as to improve coupling strategies going forward.

In the coming 5 years, AMWG will undertake the following developments to advance CESM science as well as to address the needs of the broader research community: i) increased vertical resolution and vertical extent to deliver a unified troposphere-middle atmosphere model for CMIP-class applications; ii) dynamical core (dycore) development and evaluation including nonhydrostatic options; iii) improved model physics including updated convection and boundary layer processes; iv) variable resolution (VR) configurations with regional refinement; and v) infrastructure development to streamline coupling as well as to assist community with use of specialized model configurations.

Vertical resolution and extent

A major new feature of the next version of CAM will be an enhanced vertical resolution and increased model lid height. CESM2(CAM6) has 32 levels in the vertical with a model lid height of about 40 km while CESM2(WACCM6) has 70 layers and a model lid height of about 140 km. In the next *climate workhorse* version of CAM (hereafter CAM7), the vertical grid will be modernized with the following characteristics: a higher model lid than CESM2(CAM6) but lower than CESM2(WACCM6); an enhanced vertical resolution in the free troposphere and lower stratosphere; an enhanced vertical resolution in the boundary layer, and a lowering of the lowest model level. A model lid at about 80 km is considered optimum to produce a reasonable representation of the stratospheric polar vortices while being low enough that the model can still be initialized from observation-based reanalysis products for seasonal-to-decadal prediction purposes. The enhanced vertical resolution in the free troposphere and lower stratosphere is required primarily to improve the representation of vertical propagating waves that are important for driving stratospheric variability. The enhanced resolution in the boundary layer will better represent profiles of moisture, temperature, and clouds in that region and the lowering of the lowest model level to about 18 m (from 50 m currently) brings the surface layer into the region in which Monin-Obhukov theory is more valid. A companion grid with matching resolution in the lower stratosphere and troposphere but with a lower lid is also being developed for more efficient use as a tropospheric physics development configuration and for longer, less expensive simulations. The vertical resolution enhancements discussed above are thought to be complementary to anticipated configurations with high horizontal resolutions.

These vertical grids have currently been implemented in the SE dycore. Initial evaluation has been performed in AMIP mode, and now work in fully-coupled configurations is beginning. Remaining challenges include water vapor biases and specification of chemical boundary conditions. In addition, the development of these grids has to proceed in concert with both physics developments and the introduction of the new ocean model (see below).

Dynamical core

AMWG continues to work on developing advanced tracer transport algorithms, e.g., Conservative Semi-Lagrangian Multitracer (CSLAM) (including for water isotopes), as well as on incorporating and evaluating different dycores within the CESM infrastructure. NOAA's Finite Volume Cubed Sphere (FV3) and NCAR's MPAS dycores have both been incorporated into CESM via the SIMA framework. In addition, a non-hydrostatic version of the SE dycore (SE-NH) is being incorporated. The SE-NH dycore would accommodate the infrastructure already developed for the hydrostatic SE dycore, e.g., flexible variable resolution mesh generation and CSLAM advection. In addition, SE-NH will be developed to exploit GPU accelerators.

Model physics

Several efforts are underway in boundary layer physics development which should be incorporated into new versions of CAM within a 3 to 5-year time frame. Three CPTs are focusing on joining an eddy-diffusivity / mass-flux framework with the Cloud Layers Unified by Binormals (CLUBB) scheme currently in CAM, introducing prognostic momentum fluxes in CLUBB, and coupling land-surface heterogeneity to CLUBB. All three CPTs have made successful initial implementations in single-column configurations, and over the course of the next 3 years we expect implementation and initial assessments in climate simulations. These improvements to CLUBB provide a framework for continued development incorporating information from Large-Eddy simulations targeted at higher-resolution CAM. Advanced micro-physics are also being developed through the Parameterization of Unified Microphysics Across Scales (PUMAS) effort. Physics development is an extended process. While we anticipate many of the basic implementations to be complete within 3 years, assessing them at a variety of resolutions as well as in coupled simulations is expected to continue for 5 years.

Variable resolution (VR)

Several VR efforts are already underway with different levels of maturity. A Continental US (CONUS) configuration with a grid refinement of 12 km is already being used for chemical forecasting. A polar-focus VR grid and Greenland ice-sheet grid have also been developed to explore cryosphere processes. A study of mountain glaciers has recently begun over the Himalayas using a grid refined to 6 km. An intensive intercomparison of the Weather Research and Forecasting Model (WRF) and VR CAM over South America has also begun. We expect all these efforts to continue for the next 5 years with additional focus regions developed. Tools for easier grid generation, interpolation, and analysis are also being developed (see also Infrastructure and Coupling)

Infrastructure and coupling

AMWG is involved with infrastructure and coupling developments that aim at scientific improvement as well as toward streamlined workflows for users. In the first category are efforts to incorporate complete fluxes of enthalpy from the atmosphere to other components, and also work on the Common Community Physics Package (CCPP) to facilitate swapping and reordering parameterization codes. In addition, AMWG is helping to develop easy-to-use scripts and other infrastructure for running CAM, particularly in *simpler* configurations such as single-column or aquaplanet. Finally, infrastructure is under development that will facilitate the creation of new VR focus areas. Such infrastructure includes grid generation tools for the SE dycore, as well as *on-the-fly* interpolation of 3-dimensional meteorological and 2-dimensional boundary forcing data from arbitrary native grids. We expect this to be particularly useful in connection with CAM's nudging infrastructure to create the equivalent of a regional model.

Whole Atmosphere Model

The Whole Atmosphere Working Group (WAWG) supports the development and application of the high-top atmospheric components of CESM, including the Whole Atmosphere Community Climate Model (WACCM) and its extension into the ionosphere-thermosphere (WACCM-X). The higher model top and more extensive treatment of chemical processes enable comprehensive investigations into the interactions between climate, chemistry, and aerosols, and will continue to be essential for CAM. Inclusion of ionosphere and thermosphere processes in WACCM-X provides a self-consistent representation of meteorological, solar, and geomagnetic driving of the upper atmosphere, improving our understanding of variability in Earth's upper atmosphere.

Over the next five years, WAWG will focus on initialized predictions for chemical, subseasonal-to-seasonal (S2S), and space weather forecasts; aerosol-chemistry-transport-climate coupling through the lens of geoengineering, wildfires, and extreme forcing events; upper atmosphere variability across a range of spatial and temporal scales; a more fundamental understanding of whole atmosphere vertical transport; and contributions to international climate, chemistry, and geoengineering assessments.

Several developments are needed to support these scientific focus areas. Implementation of SE-CSLAM will considerably improve the computational efficiency of VR grids, while grid-agnostic diagnostics will preserve the scientific capabilities of CESM across dycores. New open-source community analysis and model evaluation tools are also required, especially for unstructured grids and for forecast verification. Given the high computational expense of WACCM(-X), WAWG will also benefit from GPU-focused development. Incorporation of shared community frameworks, such as Model Independent Chemistry Model (MICM) and the CCPP framework, as well as co-development of the workhorse configuration of CESM, will enable greater flexibility in model configurations and streamline model development. Currently, performing initialized forecasts is not part of the standard model release, making it difficult for users to perform initialized experiments. WAWG will codevelop configurations that support initialized prediction of both short-term chemical and space weather forecasts as well as S2S forecasts. This includes initialization from reanalyses, with the challenge that reanalysis products do not generally extend as high as the WACCM lid-height, as well as directly from DA. A central framework for model initialization will unify existing WAWG forecasts that currently use different methods.

Small-scale waves and their impacts on the middle and upper atmosphere remain poorly represented, leading to model biases and limitations on current capabilities to study whole atmosphere and space weather coupling. The continued development of high horizontal and vertical resolution versions of WACCM(-X) will permit explicit simulation of much of the wave spectrum and its impact on atmospheric dynamics, chemistry, and ionosphere instabilities. However, it will continue to be necessary to parameterize gravity waves at coarser resolutions. WAWG will focus on ways to make gravity wave parameterizations scale-aware and applicable to VR grids, account for secondary gravity wave generation, perform more realistically in the thermosphere, and include their impacts on chemistry.

At the same time, WAWG will continue to develop less computationally expensive lower resolution (order 2°) versions of WACCM and WACCM-X for paleoclimate, long-duration simulations, and large-ensemble simulations, as well as for community members with limited computational resources.

Advances in the modeling of chemical and physical processes throughout the atmosphere are also needed. Current convective parameterizations generate a stratospheric water vapor bias at higher vertical resolutions. In collaboration with AMWG, this needs to be resolved in future versions of the model to ensure that water vapor is not biased by model resolution. WAWG will also benefit from development of parameterizations that are robust to large aerosol and chemical forcings, such as those that may occur during paleoclimate and geoengineering simulations.

Development of two-way coupling with a magnetospheric model (GAMERA) in WACCM-X will improve existing space weather modelling capabilities. Combined with high-resolution simulations this will enable understanding of meteorological and geomagnetically induced mesoscale processes in the upper atmosphere, including the formation of ionospheric instabilities. Adoption of the MPAS non-hydrostatic dynamical core will be explored to further high-resolution modeling capabilities. Continued development of DA capabilities in the middle-upper atmosphere will enable improved understanding of physical processes as well as the capability to perform initialized forecasts for investigating the predictability of the middle-upper atmosphere.

Atmospheric Chemistry

CESM provides a coupled chemistry-climate and chemistry-weather model that includes leading-edge representation of chemistry and aerosols for the troposphere and stratosphere. The planned developments related to chemistry and aerosols will allow continued and enhanced studies of the interactions between climate / weather, chemistry, and aerosols, with coupling to the land, ice, and ocean. The capability for VR simulations including detailed chemistry with SE and MPAS dycores, will allow global-to-regional-to-local downscaling of long-range transported air pollution within a single model. CESM will continue to provide a framework for DA of chemical composition, including multi-instance capabilities for ensemble simulations. Tools for DA and advanced statistical analysis for the comparison of simulations with observations are important to support the model evaluation and the understanding of the modeled atmospheric composition. In particular, it will allow identification of limitations in the model chemistry and emissions, leading to improved chemical forecasts as well as improved and faster model initialization overall.

The representation of chemistry and aerosols in CESM will continue to be developed under the framework of Multi-Scale Infrastructure for Chemistry and Aerosols (MUSICA), which builds on the modular framework of SIMA. MUSICA will allow greater flexibility in the choice of chemical mechanisms and aerosol schemes, as well as the physical processes affecting atmospheric composition, e.g., deposition and scavenging.

There is a desire in the CESM chemistry-climate community to have both more complex and cheaper representations of chemistry and aerosols. Particularly for present-day analyses, there is a need for more detailed representations of aerosols and chemistry, including more specific speciation, mixing state, and size distribution of aerosols, more detailed volatile organic compounds (VOC) chemistry for ozone and secondary organic aerosol (SOA) formation, which can be evaluated with intensive field campaign observations of numerous compounds simultaneously. The option for more detailed aerosol models, such as the sectional aerosol model CARMA, will be incorporated and evaluated. However, for long climate simulations, simpler chemical mechanisms with lower computing costs will be developed.

As discussed above, CESM will explore different horizontal (including variable) and vertical resolutions and the resulting performance of the model, from large scale processes to regional and local effects on chemistry and aerosols, and the impact on climate. Different dynamical cores need to be carefully evaluated for the behavior of all physical parameterizations, including gravity wave tuning, and their impacts on chemical and aerosol distributions. Efficient methods for tracer transport (e.g., SE-CSLAM) are needed to reduce the costs of more complex chemistry and aerosols. As higher resolutions are used, the representation of chemistry and aerosols, their emissions, and their interaction with clouds may need to be refined and updated.

Further development is needed to improve the coupling between the atmosphere, land, ocean, and cryosphere and to provide better representations of dust, fire, and ocean emissions of sea spray aerosols and dimethyl sulfate, deposition of black carbon, brown carbon, and dust on the cryosphere. In the upper troposphere and lower stratosphere, the representation of sulfate aerosols and ice nucleation needs to be improved for geoengineering studies. Heterogeneous sulfate formation on aerosol surfaces in polluted haze conditions needs to be assessed and addressed, if needed.

There will be a significant improvement in the quality and the precision of Earth observations in the coming 5 years, such as new satellite observations. Efforts will focus on integration of those observations in an efficient way in the coupled model, for instance by facilitating the use of advanced mathematical algorithms such as DA and ML. This will in turn help to diagnose model deficiencies in the physics and chemistry, as well as to improve the computational efficiency. There will be a significant focus on improving the predictive capability of CAM-chem for air quality applications. This requires improving the performance with meteorological nudging to reanalysis, and with DA.

Land Model

CLM is classically used as a tool to integrate terrestrial contributions and responses to weather, climate variability, and climate change. Today, land models such as CLM are increasingly expected to provide insight into climate and weather impacts on societally relevant quantities such as water availability, crop and timber yields, wildfire risk, human heat stress, and other ecosystem services (Bonan and Doney 2018). Development plans stem from needed model requirements to achieve these dual objectives as well as the need to enable the model to be applied to pressing research questions related to: i) ecosystem vulnerability to global change and feedbacks to global change from the terrestrial carbon cycle; ii) identification of sources of weather, climate, and environmental predictability from land processes, including those related to landscape heterogeneity; iii) ecological prediction and forecasting; iv) understanding the broad range of impacts of land use and land-use change on climate, carbon, water, and extremes; and v) water and food security in the contexts of climate change, climate variability, and extreme weather.

LMWG plans and development priorities are determined in concert with those for the Community Terrestrial Systems Model (CTSM). CTSM is a unification of several land modeling efforts (principally CLM and the Noah-Multiparameterization Land Surface Model, Noah-MP, used in WRF) and is being designed for broad applicability for research into climate, weather, water, and ecosystems. CLM no longer exists as its own entity and is now and will be a configuration of CTSM (CTSM-CLM). CTSM is being co-developed by CGD and the Research Application Laboratory (RAL) at NCAR in collaboration with national and international partners. Decisions about the configuration of future default versions of CTSM-CLM will be the responsibility of LMWG and the CESM SSC.

To develop a model capable of addressing the scientific goals outlined above, LMWG has an ambitious model development program with an emphasis on the following key areas.

Implementation and parameterization of the Functionally Assembled Terrestrial Ecosystem Simulator (FATES) ecosystem demography model

The goal is to include FATES, which is developed in collaboration with the DOE and European partners, as the primary vegetation model of CTSM-CLM for CESM3. FATES is a cohort model of vegetation competition and co-existence, allowing a representation of the biosphere which accounts for the division of the land surface into successional stages, and for competition for light between height structured cohorts of representative trees of various plant functional types. FATES is expected to provide substantially greater realism in terms of predictions of future ecosystem states and fluxes. By explicitly representing disturbance and other impacts, it is also expected to help address questions of ecosystem vulnerability. Simpler versions including the current vegetation and biogeochemistry (BGC) and prescribed vegetation (SP) schemes will be maintained for use in applications for which detailed ecosystem functioning is not required.

Representative hillslopes and role of sub-grid heterogeneity on land-atmosphere interactions

The inclusion of representative hillslopes will revolutionize the depiction of landscape heterogeneity through simulation of lateral water flow along elevation and water table gradients at scales (100s of m) that are appropriate to the natural system. Impacts of slope, aspect, and co-variability of vegetation type with hillslope / riparian zone position are also represented. An initial implementation is in place and research efforts over the next several years will focus on definition of input datasets that define dominant hillslopes and their characteristics within each grid cell across the global domain. FATES combined with representative hillslopes will be a powerful tool to examine interactions between water and ecosystem structure. Further, existing models do not account for the impact of strong heterogeneity in land fluxes on boundary layer and convection processes. A CPT is developing methods for the transfer and use of heterogeneous flux information from the land to the atmosphere.

Agriculture and water management

Improved agriculture and water management allows for more detailed and informative examination of the impacts of climate change on food and water security. It provides the platform for research into land management as a climate mitigation tool and evaluates tradeoffs arising from different food, water, and energy management decisions. LMWG is working on many projects to increase the realism of agricultural systems through improvements in crop phenology, representing processes such as tillage, shifting cultivation, spatially-explicit planting dates, biofuel crop parameterizations, manure and ammonia volatilization, and multiple irrigation methods. A new vector-based river model will be incorporated to permit explicit simulation of lake, reservoir, and stream interactions, which then permits capability to simulate reservoir management and, in combination with groundwater withdrawal, a closed irrigation budget.

Global parameter estimation

Development of an optimized global parameter estimation technique using emulators and ML is underway. Significant efforts have gone into developing the infrastructure and expertise to conduct global parameter perturbation experiments and ML techniques to explore parameter sensitivity and optimization of the model. This work also required the implementation of a matrix solution for carbon and nitrogen which substantially accelerates model spin-up and allows for unique diagnostics such as carbon residence time and attribution. We will develop an optimized land parameter set for CESM3 using these tools.

Improved ease of use to broaden the applicability of CTSM

The CTSM development team recognizes that a key requirement of success is model *ease-of-use* through enhanced flexibility of model construction (e.g., runtime changes to number of plant functional types and land units, range of model complexity, multi-physics options) and spatial disaggregation (rectilinear, unstructured, and catchment grids). This includes the implementation of the Simple Land Interface Model (SLIM) into the CESM codebase. SLIM is an idealized, simplified, and highly controllable land model with which users can explicitly control albedo, evaporative resistance, and surface roughness for studies of how specific regional land properties exert influence on the atmosphere. Also included within *ease-of-use* needs are better tutorials, diagnostics, data analysis workflows (e.g., subgrid or FATES output), and simplified tool chains to generate input datasets and initial conditions.

Multi-layer canopy

A new canopy flux model is being developed for CLM. The model updates the existing canopy flux parameterization for recent developments in leaf gas exchange, plant hydraulics, and canopy-induced turbulence. The equation set uses a fully implicit solution to calculate leaf temperature and fluxes, soil surface temperature and fluxes, canopy air temperature, and canopy air vapor pressure and is more numerically robust than CLM, which diagnoses, rather than prognoses, the canopy air space and can require many iterations to converge on a solution. An advantage of the multilayer implementation (in contrast with the single-layer used in CLM) is that the model distinguishes between the microclimate within the canopy and the coupling above the canopy with the boundary layer. This is particularly important in tall forests.

Other developments

Incorporation of water isotopes is an important, on-going need. This requires refactoring of the hydrology code in CLM. Another effort concerns the development and evaluation of a microbial explicit soil BGC model (MIMICS) which is expected to improve the ecological realism of soil BGC fluxes.

Ocean Model

The CESM ocean component is designed to address specific science objectives as determined within the Ocean Model Working Group (OMWG) and the broader CESM community. The primary goals of OMWG are to advance the capability and fidelity of the CESM ocean component and to conduct curiosity-driven research using CESM to advance our understanding of ocean processes, the role of the ocean in the Earth system, and its interactions with other Earth system components. The strategic plans for OMWG over the next five-year period are strongly driven by the technical and scientific requirements and opportunities presented by the transition of the CESM ocean component dynamical core from the legacy Parallel Ocean Program version 2 (POP2) to MOM6[10].

The focal point of the OMWG efforts will be to provide a world-leading ocean climate model suite – at a variety of resolutions – based on MOM6. Over the past two years, OMWG has implemented a baseline configuration of MOM6 with a nominal horizontal resolution of 2/3° that conforms to the interface requirements of the CESM system. This configuration is currently being run and evaluated in both forced ocean – sea ice and fully coupled configurations. Work in the near term will focus on this configuration, bias reduction, implementing the few remaining physical processes developed in POP2 that are not yet available in MOM6, e.g., the estuary box model and aspects of coupling of ocean mixing to wind waves, leveraging MOM6's advanced vertical coordinate representation, and incorporation of novel, scale-aware parameterizations that emerge from the Eddy Energetics CPT.

The CESM community evinces strong interest in using a range of ocean model resolutions for different scientific purposes. Higher resolution configurations in both the eddy permitting (20-30 km nominal resolution) and eddy resolving (10 km or finer resolution) regimes are of interest for applications in prediction and ocean process investigations. OMWG will work closely with the CPT to provide a seamless hierarchy of configurations across this resolution range. At the other extreme, a lower resolution and lower-cost configuration is of interest to a segment of the user community for applications in BGC, paleoclimate, and land ice-ocean coupling. OMWG will collaborate with other WGs and the university community to facilitate this effort. There is also strong interest in the community for development of an ocean component for use in the CESM lower-cost / specialized model suite. Such a model would facilitate research in fundamental questions in climate dynamics and provide a computationally efficient platform for use in an academic setting, where past collaborative applications such as parameterization development and pedagogical simulations have traditionally required NCAR resources. An effort led by the university community and coordinated through OMWG will develop MOM6-based configurations suitable for these applications. Additionally, we will aim to implement water isotopes in MOM6 in collaboration with PaleoCWG.

A principal development between CESM1 and CESM2 was the introduction of NOAA WaveWatch-III as a new system component. This prognostic wave model is used in CESM2 to study changes in wave climate and to provide the forcing data for a parameterization of Langmuir turbulence in the upper ocean. Work to upgrade to the latest version of WaveWatch-III is ongoing and will provide a number of new capabilities: the ability to run waves on a grid matching all present and planned ocean model grids; an interface to the wave-averaged Boussinesq momentum equations and new boundary layer parameterizations in MOM6; the ability to simulate waves in an ice-free Arctic; and the

[10] With its natural freshwater surface flux boundary conditions, MOM6 allows explicit simulation of steric and eustatic sea level changes, including sea level rise due to glacial melt.

ability to simulate wave – sea ice interactions that were recently demonstrated to be a significant factor in floe size distribution dynamics.

Along with the transition to a new ocean component, a transition in ocean model analysis tools is required, to accommodate both the differences in the model formulation and output conventions, but more importantly to better provide a flexible, extensible, and scalable set of research tools suited to the increasing volumes of data and changes in computing and storage environments. An effort to accomplish this by exploiting the rapidly evolving ecosystem of python-based tools such as Pangeo and Xgcm is a high priority within OMWG. These approaches will enable a wider collaborative network for ocean simulations than possible in previous OMWG efforts. In parallel with the development of CESM-MOM6 and the associated workflow tools, we will deliver documentation and training to the CESM community to facilitate and expedite the transition to MOM6. The intention is to provide both the MOM6 model and accompanying tools and support incrementally, first to early adopters in exchange for constructive criticism, rather than waiting for the release of the final CESM3. A first version of CESM-MOM6 was released in CESM2.2.

Sea Ice Model

For sea ice model development, a primary focus of the CESM Project has been on improving the representation of aspects of the sea ice system that influence ice-ocean-atmosphere interactions and climate feedbacks. During the next five years, model development efforts will continue in these areas as discussed below. Additional attention will be given to factors important for Earth system prediction, including better integration of models and observations through DA, and to aspects of sea ice important for actionable science, including developments important for high-resolution simulation.

Over the course of this Plan, the sea ice component of CESM will use the CICE consortium model. This is a community model that is overseen by an interagency consortium group of stakeholders and primary developers and is under active development by the larger research community. As of Fall 2022, CICE6 is a default component in the newer CESM2 tags. Ongoing developments with CICE6 will address improved coupling of sea ice with MOM6. The introduction of the CICE6 component also allows for numerous new physics options within CESM as described below. On a longer timescale, parameterization developments are targeted at improving aspects of the sea ice that affect Earth system coupling, climate system feedbacks, and predictive capabilities.

Improvements are planned for the coupling of freshwater, salt, and heat between the sea ice and ocean. This includes the coupling of the sea ice prognostic salinity (Turner and Hunke 2015) with the ice-ocean freshwater and salt exchange, allowing for an improved representation of the role of sea ice in the hydrological system. It will also include modifications as needed to enable conservative enthalpy coupling of sea ice with other system components. To ensure better consistency with the MOM6 ocean component, developments are also underway for the CICE numerics, specifically through the incorporation of a C-grid capability within the model. It is expected that this will be available in 2023.

For the development of CESM3, sea ice model improvements will focus on advanced snow physics, the incorporation of landfast sea ice, and the inclusion of a floe size distribution model and associated wave-ice interactions. All of these are available within CICE6 with varying states of readiness. However, they have not been tested within the CESM system. The advanced snow physics (based in part on Lecomte et al. 2015 and Oleson et al. 2019) includes snow grain evolution, the influence of blowing snow, and prognostic snow density. These factors affect the optical and thermal properties of the sea ice with implications for climate feedbacks. Landfast sea ice is a new capability in the model (Lemieux et al. 2016) designed to simulate the process where sea ice grows thick enough to become grounded on the ocean floor. Landfast ice influences ice-ocean-atmosphere fluxes and is used by coastal communities for travel and hunting and will be particularly important in higher resolution simulations which better resolve the shallow shelf regions in both hemispheres. A major development within CICE is the inclusion of a floe-size distribution that simulates a distribution of sea ice floes (Roach et al. 2018). This influences lateral melting of sea ice, with implications for the albedo feedback, and enables the simulation of wave-ice interactions. To simulate sea ice - wave interaction will require coupling with the prognostic wave model discussed in the ocean model developments above. We expect that these new physics options will be used in CESM3 and anticipate that they will be available by Summer 2023. The coupling of sea ice biogeochemistry available in CICE6 with the marine ecosystem will also be considered. This would enable better simulation of the polar marine ecosystem and its role in the carbon cycle.

Sea ice exhibits high spatial heterogeneity which influences the surface albedo and sea ice thermal properties with implications for climate feedbacks. With the availability of new field observations (e.g., from MOSAiC), and high-resolution remotely sensed data (e.g., from IceSAT2), there are new opportunities for improving the parameterization of the spatial heterogeneity and time evolution of sea ice properties. During the lifetime of this Plan, new developments will focus on improving factors affecting the surface albedo evolution including sea ice optical properties, melt pond characteristics and factors driving melt pond evolution, snow properties and their influence on the albedo, and improved shortwave radiative transfer including better spectral resolution that is more compatible with the atmospheric model. Additional work is underway to use ML to better represent the influence of snow heterogeneity on its effective conductivity and consequent ice-atmosphere heat fluxes. These developments will all be fed back into the CICE consortium model, specifically through development of the Icepack column physics.

Improved integration of models and observations are also under development. This includes DA capabilities through the coupling of CICE with the Data Assimilation Research Testbed (DART) framework, which will enable initialized sea ice predictions.

Developments to enable better comparisons between simulation conditions and observed quantities are also being considered for example through the incorporation of satellite emulators. Another effort concerns incorporation of water isotopes. With the community nature of CICE, additional developments from the broader research and model development communities are also likely to come online within the next five years and will be considered for future CESM configurations.

Land-Ice Model

The Land Ice Working Group (LIWG) will continue working toward fully interactive coupling of ice sheets with the land, atmosphere, and ocean. CESM2 was one of the first Earth system models to support a dynamic Greenland Ice Sheet (GrIS) coupled to the land and atmosphere. CESM3 will add an interactive Antarctic Ice Sheet (AIS), along with improved physical processes in the Community Ice Sheet Model (CISM). These innovations will enable first-of-a-kind simulations to improve ice-sheet and sea-level projections.

As a result of recent software engineering advances, CESM can simulate multiple ice sheets, including AIS, for the first time. Hooks are in place for passing ice draft, ocean temperature and salinity, and / or sub-ice-shelf melt rates between MOM6 and CISM. MOM6 can simulate ocean circulation and melting beneath ice shelves – a major advance on the simple basal melt schemes used in current ice sheet models. Meanwhile, LIWG is developing new parameterizations in CISM for basal friction, subglacial hydrology, and damage-based iceberg calving. Also, CISM is being adapted as a mountain glacier model, to study High Mountain Asia and other regions where ongoing glacier retreat threatens water supplies downstream. To aid model validation, LIWG is building a comprehensive land-ice diagnostics package, along with more robust scripting for coupled ice-sheet configurations.

With these developments, CESM will be able to simulate coupled marine ice sheets, including AIS – Southern Ocean interactions that dominate the uncertainty in projected sea level rise. According to the IPCC Sixth Assessment Report, global mean sea level will likely rise 28-55 cm by 2100 for low emissions, and 62-102 cm for high emissions, with leading contributions from ice sheets and glaciers. The likely range, however, does not include ice sheet processes characterized by deep uncertainty, including marine ice cliff instability and sub-shelf melting driven by ocean warming. CESM will be one of the first Earth system models to represent these processes.

The paleoclimate record can help constrain future ice-sheet projections. The LIWG will work with the Paleoclimate Working Group (PaleoCWG) to model interactive ice sheets in past warm and cold climates. Projects now under way will address Antarctic evolution during the Last Interglacial, as well as Laurentide retreat after the Last Glacial Maximum. Such simulations of the last glacial cycle represent Grand Challenge simulations, involving not only interactive ice sheets, but also evolving land surface and vegetation and interactive carbon cycle. To support long transient simulations with coupled ice sheets, we plan to work with a scientifically-validated version of CESM, perhaps with a 2° resolution for CAM and MOM6, with a throughput of at least 50 simulated years per day.

Ice sheet simulations are only as realistic as the surface mass balance (SMB) provided by the land and atmosphere models. The surface climate of ice sheets in CESM2 has some significant biases, including excessive snowfall in southern Greenland and East Antarctica. During CESM3 development, LIWG will work with other WGs to diagnose and reduce these biases. VR CAM, which can better resolve orographic forcing in regions of interest, shows promise for improving precipitation.

LIWG will cultivate relationships with groups that can benefit from CESM-CISM development and simulations. We will continue to support the national and international academic communities with a broadly capable, user-friendly, ice-sheet-enabled CESM. We will work with other modeling groups, including GFDL and NorESM, that are working toward ice-sheet coupling and plan to adopt CESM land-ice components. LIWG also aims to support mitigation and adaptation decisions by communicating useful, timely results to policymakers and coastal stakeholders. LIWG is already participating in outreach to stakeholders and will be part of a broader effort to translate CESM results into actionable science.

Biogeochemistry

The Biogeochemistry Working Group (BGCWG) has led the integration of terrestrial and marine biogeochemistry and coupling of that biogeochemistry across components of the Earth system into what is now CESM. This interaction between systems including interactive biogeochemistry is critical to enabling the *Earth system* aspect of CESM (Bonan and Doney 2018). The coupling between systems and the implications of that coupling are a focus of BGCWG. Land and ocean ecosystems influence climate through a variety of biogeophysical and biogeochemical pathways. Interactions between climate and ecosystem processes, especially in response to human modification of ecosystems and atmospheric CO_2 growth as well as glacial-interglacial cycles, produce a rich array of climate forcings and feedbacks that amplify or diminish climate change. Biota also modulate regional patterns of climate change. Ecosystems are the focus of many carbon sequestration approaches for mitigating climate change, and are the central elements of potential climate impacts associated with food security, water resources, human health, and biodiversity. However, the magnitude of these climate-ecosystem interactions is not well constrained, and are critical scientific unknowns affecting the skill of future climate projections.

Ocean biogeochemistry applications and development

Ocean biogeochemistry is simulated in CESM by the Marine Biogeochemistry Library (MARBL), which provides a flexible, highly configurable representation of the lower trophic levels of marine ecosystems and associated elemental cycling (Long et al. 2021). This flexibility is important to enable model configurations suitable for addressing a range of important societally-relevant research questions. Three specific areas of focus for the CESM community include carbon uptake and storage, supporting marine ecosystem and fisheries management, and supporting the development and implementation of ocean-based technologies for carbon dioxide removal (CDR). Below we provide a brief overview of each of these topics and identify key areas for development.

Carbon uptake and storage: The ocean comprises a major sink for anthropogenic CO_2 and also stores vast quantities of natural carbon. MARBL represents the set of chemical and biological processes that mediate this carbon uptake and storage in the context of three-dimensional ocean circulation and mixing. Continued development to improve these processes will be important over the coming years to ensure that CESM retains cutting-edge status in its capacity to represent changes in the ocean carbon cycle under variations in climate. Specific development initiatives include improving the representation of the diversity of phytoplankton and zooplankton functional types and their underlying physiology. For example, phytoplankton community composition, grazing relationships, and variations in nutrient uptake stoichiometry are important controls on the efficiency of the biological pump. Further, a key improvement needed in MARBL is an explicit representation of sinking particulate matter, which is essential to ensure mechanistic representation of variations in the vertical transfer efficiency of the biological pump. Notably, for example, MARBL's current implicit formulation ignores the role of particle size in determining sinking rates and the effects of temperature in controlling remineralization rates; these variables are sensitive to climate forcing and have the potential to yield important changes in export production under novel climate conditions.

Marine ecosystems: The lower-trophic levels of marine ecosystems represented by MARBL underpin marine food webs, including those that sustain fisheries. Marine ecosystems are exquisitely sensitive to climate forcing, manifesting in part from variations in the nature and quality of biological production at these lower trophic levels. This has motivated the implementation of the Fisheries Size and Functional Type (FEISTY; Petrik et al. 2019) model in CESM, which provides a capacity to explicitly simulate spatial and temporal variations in the distribution of fish biomass. FEISTY leverages the representation of lower trophic level dynamics provided by MARBL, enabling an end-to-end framework for explicit predictions of variations in fisheries-relevant biomass from climate forcing and other stressors. Continued development of MARBL configurations to support FEISTY, as well as finalization of the FEISTY implementation in MOM6 are key strategic imperatives.

Ocean carbon dioxide removal: Scientific consensus has concluded that stabilization of global temperatures requires both dramatic cuts to emissions and the active removal of large quantities of carbon dioxide from the atmosphere. A new industry is developing ocean-based technologies to remove CO_2 from the atmosphere and store it in ocean reservoirs for centuries, seeking to sell these offtakes to buyers of carbon removals. However, there are several outstanding questions regarding the efficacy of ocean CDR technologies, their potential for generating marine ecosystem impacts, and how their net effects can be quantified in the context of selling carbon removals. Key model development initiatives to support CDR research include instrumenting CESM to accept key CDR-related forcing terms, such as alkalinity additions. Further, given that seaweed cultivation is an area of active interest for ocean CDR, there is a need to implement a capacity to simulate macroalgae cultivation.

Each of these priority research areas include phenomena that exhibit strong interactions with ocean physical dynamics. Global models, however, while useful for a myriad of questions, are too computationally expensive to run at fine enough horizontal resolution to provide high-fidelity representations of ocean flows. This implies a requirement for regional models, which enable capturing critical phenomena such as tides, coastal currents, and upwelling, for example. A strategic imperative for CESM, therefore, is to develop regional domains with MOM6 as well as the coupling infrastructure necessary to flexibly support these – including in two-way nested configurations.

Ocean-sea ice biogeochemistry coupling

A goal of CESM is to include enhanced coupling between the biogeochemistry parameterizations in different components of the coupled model. CICE6 includes a biogeochemistry model for the interior of the sea ice column, extending the skeletal model present in its previous version. BGCWG, in partnership with PCWG, plans to couple the CICE biogeochemistry model to the BGC model in the ocean model. This coupling has the potential to affect surface exchange of CO_2 with the atmosphere, which is climatically relevant, and primary productivity in the Arctic. As primary productivity is the base of the ocean food web, this latter change has societal relevance.

Coupled carbon isotopes

While recent advances in CESM have improved the skill of model's simulation of atmospheric CO_2, e.g., the seasonal cycle at high northern latitudes, net CO_2 atmospheric convolves imprints of terrestrial and oceanic processes. These processes have different footprints on the isotopic composition of atmospheric CO_2, so comparing modeled isotopes of atmospheric CO_2 to observations is a stronger test of the model. The ocean and land BGC models both include options for simulating ^{13}C and ^{14}C. BGCWG plans to introduce these isotopes into the atmospheric model, and couple the isotopes across the land, ocean, and atmosphere models. This will enable tighter validation against observations.

Data assimilation capabilities for biogeochemistry

The DART team in CISL has extensive experience applying Ensemble Kalman filter based DA to geophysical models. BGCWG plans to partner with the DART team to apply these tools to biogeochemical models in CESM. A target application is parameter estimation in the ocean BGC model. Parameters in the model have been selected by expert judgment, using a handful of parameter perturbation experiments. As more processes are added to the model, this manual process is becoming a weakness in the model development process. To mitigate this, we will explore the application of automated parameter optimization strategies to assist this process. The goal of this effort is to make the model development process more robust and transparent. Another application of DA is to generate estimates of the state of the coupled carbon system, including surface fluxes of CO_2, natural and anthropogenic. A use case of this state estimation is to verify that mitigation efforts are being implemented and that they are having the desired effect on atmospheric CO_2 levels.

Sensitivity of carbon-climate system to model assumptions and parameter choices

Expected carbon uptake by land and ocean systems under future climate remains highly uncertain, particularly over land. Prior work by the Hadley Centre has shown that small variations in assumptions about carbon cycle processes have disproportionately large impacts on atmospheric CO_2 concentrations in the future. Across a range of plausible carbon cycle related parameter values, Booth et al. (2012) finds a spread of more than 400 ppm CO_2 in the atmosphere for a *single emissions scenario*. The parametric uncertainty of carbon cycle processes is thus likely to be large, and remains entirely unquantified for CESM. To address this, we plan to run a set of perturbed parameter simulations that will complement similar projects occurring in LMWG (CLM Perturbed Parameter Experiments, PPE) and AMWG. What is unique with the BGCWG contribution is that we will target parameters likely to influence CO_2 concentrations. These can be preliminarily identified for the land model from the effort of LMWG's offline ensemble of PPE runs. The outcome is a better understanding of the model processes which drive carbon cycle uncertainty and a different framework for identifying the relative importance of different parameters and the selection of their assigned values.

Idealized benchmark configurations to ensure that the model is stable with respect to a wider range of future emissions scenarios

While scientists have previously used scenarios with continually ramping emissions to describe "business as usual", insights from integrated assessment models and the nationally determined contributions made for the Paris Agreement / Glasgow Pact suggest that emissions growth may slow, stabilize at net zero, or even turn negative during the 21st century. Depending on how the transitions between these emissions regimes are represented, artifacts may appear in the coupled simulations of land and ocean carbon sinks. Most of the global modeling done to consider negative emissions has done so in a concentration-driven, rather than emissions-driven framework. In preparation for a shift to these runs in the emissions-driven, fully coupled BGC configuration, we will develop benchmarks for emission-driven simulations to ensure that there aren't discontinuities or unphysical nonlinearities associated with large changes in emissions. By characterizing the BGC response to patterns of emissions changes in the development phase, we will ensure that MIP runs using CESM3 will provide useful, physically plausible insights into land and ocean sinks and related variables, rather than being characterized by numerical artifacts. This activity will build capacity to look both at the feedbacks and the long-term evolution of the biosphere.

Software Engineering

Software engineering priorities are determined to ensure that CESM science priorities are addressed in a timely manner. CESM software engineers will continue to spend much of their time integrating new science features into the model. This includes both features whose development is led by the Software Engineering Working Group (SEWG) – such as the addition of water isotopes across CESM – and features developed by scientists within the CESM community. Substantial work is often needed to migrate code from a form that works for its initial developers to a form that is production-ready, usable by a wide community, and works correctly in the wide range of possible CESM configurations. As CESM software engineers integrate new developments, they will review them for correctness, including their integration with other modules; add tests to ensure that the new code meets requirements like exact restarts and continues to work correctly moving forward; and rework the code as needed to ensure that it is readable, extensible, maintainable, and performance portable to a variety of architectures. In addition, the SEWG will continue to develop the core Python and Fortran infrastructure components of CESM, such as the CIME Case Control System, to ensure that CESM remains easy to use, port, and customize.

An important area of development over the next few years will be making it easier to run CESM in ways that have previously been difficult. This includes having new initialization capabilities for the system (required for Earth system prediction experiments), interaction with DA utilities and the ability to easily add new model grids. These will leverage capabilities available through CESM's new mediator (i.e., flux coupler), the Community Mediator for Earth Prediction Systems (CMEPS), and new data models, the Community Data Models for Earth Prediction Systems (CDEPS), which are built on top of ESMF. In addition, SEWG will improve the usability of tools for creating resolution-dependent boundary and initial condition files for each component.

Advancing ESMF National Unified Operational Prediction Capability (NUOPC) infrastructure is critical to bringing these and other new capabilities into CESM. The exchange grid was recently introduced and will be further validated and optimized. Support for implicit coupling is coming to the forefront as well, for example, to reduce model instabilities seen in the CLUBB-CTSM coupling, and to support continual increases in vertical level resolution in the atmosphere and land models. NUOPC – Joint Effort for Data assimilation Integration (JEDI) interoperability is also emerging as an important priority to provide the infrastructure needed for coupled DA, such as support for JEDI driving single model components as well as fully coupled systems through a unified interface.

Many users of CESM, especially at universities, want to use the model in simpler configurations, such as single-column simulations, aquaplanet configurations, or other idealized configurations. In addition to being much less computationally expensive, these idealized configurations often lend themselves better to studying individual processes. SEWG will continue to develop tools to facilitate determining the simpler model configurations that are available with a CESM snapshot and to easily set up experiments with these configurations.

Another priority for CESM over the next few years is to ensure that the model can run at exascale resolutions such as global 3 km across the modeling system. Memory scalability bottlenecks across the system need to be removed and performance scalability must also be ensured. Work on this is already underway. This effort will also tie in to the CESM accelerator efforts discussed above.

Another large area of emphasis for SEWG over the next few years will be facilitating the postprocessing and analysis of CESM output. Motivated by the end of life of NCL and the rapidly growing ecosystem of data analysis tools in Python, SEWG members are working with other WGs to rewrite the aging component diagnostics packages in Python. SEWG will also coordinate efforts to address some long-standing idiosyncrasies with CESM output, making the analysis of this output less error-prone. With data storage increasingly becoming a bottleneck, SEWG is also working on a few projects to reduce data output volume. One promising project involves applying lossy compression to CESM output. Research is underway to evaluate compression algorithms that reduce data volume significantly while having negligible impact on model results. SEWG hopes to include some level of lossy compression by default in future CESM workflows over the current default of lossless compression.

New technologies such as cloud computing and containers are also offering new opportunities to both simplify the use of CESM and democratize access to hardware infrastructure for running it. Both technologies offer an ability to preconfigure a standardized modeling environment that is ready to run, making it much easier to not only use, but also to develop common workflows and training materials for the community. In addition to these developments, SEWG will create tools to automate the deployment of complex, ever-changing cloud resources, providing the community with simple, vendor-neutral methods for using the cloud and optimizing costs.

Software engineering choices for CESM will take into consideration the intention to collaborate with NOAA as expressed in the Memorandum of Agreement, signed between NOAA and UCAR in 2019. This agreement lays out the intention for the two organizations to benefit from each other by developing and using common modeling infrastructures. In particular, CESM and the NOAA Unified Forecast System (UFS) will share and continue to jointly develop infrastructure for inter-component coupling (e.g., CMEPS), for intra-component coupling (e.g., the CCPP framework), for hierarchical system development and testing (e.g., CDEPS), and for code repository management.

Data Assimilation

Increasing computing power and advances in the sophistication of Earth system models and DA algorithms have put DA – once primarily the province of short-term numerical weather prediction – within reach across Earth system components and time scales. Beyond comparing models and observations, DA incorporates observations directly into model trajectories and dynamics. As discussed in previous sections, DA approaches can improve model initialization for predictability and prediction studies; generate climate reanalyses, including chemical composition, that are consistent with both model dynamics and observations; and provide a framework for objectively constraining uncertain model parameters and processes, including using ML. Recent and ongoing efforts have established and expanded DA capabilities within CESM components, including using CLM5 (Raczka et al. 2021), POP2 (Karspeck et al. 2018; Castruccio et al. 2020), CAM6 (Raeder et al. 2021), and CICE5 (Zhang et al. 2018). Combining these efforts into a unified CESM configuration with ongoing support will provide unique opportunities for coupled DA and integrative, data-constrained Earth system science. Accordingly, we will develop a workhorse CESM3 configuration that facilitates DA capabilities across all components to allow data constraints among and between physical domains. This platform will be tailored to be an accessible starting point for interdisciplinary coupled DA research and for developing novel DA systems. Applications include:

<u>Earth system predictability and coupled processes:</u> Explicit incorporation of data constraints in CESM will accelerate research on several frontiers of actionable, societally-relevant science. First, initializing ESPs from coupled reanalyses can reduce drifts and initial model shock (relative to initializing from observations or uncoupled models) because DA states already bear the dynamical imprint of the coupled model attractor. Incorporating data constraints across components is expected to improve forecasts and provide a novel lens on the mechanisms governing predictability across time scales and Earth system components. Second, the carbon cycle is a fundamentally coupled process. Simultaneously constraining the ocean, atmosphere, and terrestrial biosphere to available data on carbon fluxes and concentrations could enable breakthroughs in carbon cycle prediction and important insights into geoengineering strategies.

<u>Parameter estimation and model improvement:</u> Underlying structural and parametric errors in Earth system models can be dominant sources of model error, including manifesting as persistent model biases. DA approaches offer multiple avenues towards reducing these biases and, more broadly, a paradigm for data-driven model improvement. As one approach, ensemble parameter estimation adjusts time-constant or evolving quantities to improve model data misfit; we will investigate this approach in concert with model state acceleration procedures, e.g., Newton-Krylov approaches, implemented in CESM by Lindsay (2017), to reduce time-mean bias in BGC quantities (also see Biogeochemistry section). As part of the M2LinES project, ML algorithms will be trained on DA increments (changes made to fit data) to explore novel parameterizations for reducing persistent North Atlantic SST biases.

<u>Advancing DA techniques for Earth system science:</u> Assimilating observations for coupled climate problems raises challenges that are distinct from those in traditional numerical weather prediction. For instance, sparse observations of systems with long dynamical timescales may be best fit to data by changing model initial conditions. Computational costs (typically 10-100x higher than for forward models) will remain a challenge for the foreseeable future. Finally, as noted above, climate model errors (rather than chaotic evolution) can dominate model-data misfits.

We will continue to develop techniques tailored to the characteristic challenges of Earth system DA. Using the workhorse configuration as a platform, we will advance lower-cost techniques including Ensemble Optimal Interpolation (Castruccio et al. 2020), hybrid approaches (El Gharamti 2021) and reanalyses performed sequentially across components

(O'Kane et al. 2021) to reduce costs for high-resolution applications. Multi-component DA will provide a laboratory to investigate weakly and strongly coupled DA, noting whether observations can have cross-component impacts. These developments will be made in coordination with efforts within the DART and JEDI platforms to harness current and emerging strengths of both DA systems. As a first step, we will advance capabilities for using JEDI forward operators (FOs) as external forward operators in CESM-DART, beginning by implementing the JEDI ocean skin temperature FO as an external FO in DART and MOM6. This work will leverage existing infrastructure from the Joint Center for Satellite Data Assimilation Sea-ice Ocean Coupled Assimilation project.

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