Earth and Environmental Systems Sciences Division

Strategic Plan

U.S. DEPARTMENT OF **ENERGY** | Office of Science

Office of Biological and Environmental Research

Earth and Environmental Systems Sciences Division

science.osti.gov/ber/Research/eessd

Gary Geernaert, gerald.geernaert@science.doe.gov

Atmospheric Sciences Research Area

Atmospheric System Research
asr.science.energy.gov

Shaima Nasiri, shaima.nasiri@science.doe.gov

Jeff Stehr, jeff.stehr@science.doe.gov

Ashley Williamson, Retired

Atmospheric Radiation Measurement User Facility
arm.gov

Sally McFarlane, sally.mcfarlane@science.doe.gov

Rick Petty, rick.petty@science.doe.gov

Earth and Environmental Systems Modeling Research Area

Model Development
climatemodeling.science.energy.gov

Xujing Davis, xujing.davis@science.doe.gov

Dorothy Koch*

Multisector Dynamics
climatemodeling.science.energy.gov

Bob Vallario, bob.vallario@science.doe.gov

Model Analysis
climatemodeling.science.energy.gov

Renu Joseph, renu.joseph@science.doe.gov

Environmental System Science Research Area

Subsurface Biogeochemical Research
doesbr.org

Paul Bayer, paul.bayer@science.doe.gov

Jennifer Arrigo, jennifer.arrigo@science.doe.gov

Amy Swain, amy.swain@science.doe.gov

David Lesmes*

Terrestrial Ecosystem Science
tes.science.energy.gov

Daniel Stover, daniel.stover@science.doe.gov

Environmental Molecular Sciences Laboratory
emsl.pnl.gov

Paul Bayer, paul.bayer@science.doe.gov

Data Management

Justin Hnilo, justin.hnilo@science.doe.gov

* Former program manager

2020 Update

In April 2020, the U.S. Department of Energy's Office of Science underwent an organizational change that included updating the name of the Climate and Environmental Sciences Division (CESD) within the Office of Biological and Environmental Research. The division's new name is the Earth and Environmental Systems Sciences Division (EESSD). No changes were made to the names or scope of the division's scientific programs. The cover of this strategic plan has been updated to reflect the name change to prevent any discontinuities for the scientific community. While the CESD name remains throughout the text, the document still reflects EESSD's mission, vision, scientific grand challenge topics, and implementation strategy.

Biological and Environmental Research

Earth and Environmental Systems Sciences Division

(formerly Climate and Environmental Sciences Division)

Strategic Plan
2018–2023

Prepared by the Earth and Environmental Systems Sciences Division
within the U.S. Department of Energy Office of Science
Office of Biological and Environmental Research

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U.S. DEPARTMENT OF ENERGY | Office of Science

Office of Biological and Environmental Research

Contents

Executive Summary

The Climate and Environmental Sciences Division (CESD) of the Office of Biological and Environmental Research (BER) is managed within the U.S. Department of Energy's (DOE) Office of Science. CESD is the intellectual home for fundamental research needed to address key uncertainties arising from the interactions and interdependencies of the atmospheric, terrestrial, subsurface, cryospheric, oceanic, and human-energy components of the Earth system. Using an approach to enhance system predictability, CESD-supported research strives to understand and anticipate how environmental stressors behave within a nonlinear system. These stressors, in turn, can influence the robustness and resilience of U.S. energy infrastructures. Particular emphasis also is placed on understanding how natural and human-derived factors contribute to variabilities and trends spanning local to global scales. By treating DOE environmental challenges as part of the Earth system, CESD also addresses DOE's unique concerns regarding energy contaminants and wastes. The scope of CESD process research spans scales from molecular to global and durations from nanoseconds to many decades, in order for DOE to achieve its goals involving foundational science, environment, energy, economic, and security.

Organization

CESD's research is organized around three disciplinary areas, each comprising specific research activities: **Atmospheric Sciences** includes the Atmospheric Radiation Measurement (ARM) User Facility, **Environmental System Science** includes the Environmental Molecular Sciences Laboratory (EMSL), and **Earth and Environmental Systems Modeling** includes the newly released Energy Exascale Earth System Model (E3SM). CESD also supports the **Data Management** (DM) activity, which supports the archival of data generated by Earth system models and CESD-supported field experiments; the DM activity also invests in software and data analytics capabilities for use by the scientific community.

Vision and Mission

CESD's vision is to develop an improved capability for Earth system prediction on seasonal to multidecadal time scales to inform the development of resilient U.S. energy strategies. CESD's mission is to enhance the seasonal to multidecadal predictability of the Earth system using long-term field experiments, DOE user facilities, modeling and simulation, uncertainty characterization, best-in-class computing, process research, and data analytics and management. The Division's mission is dedicated to providing the fundamental science needed to inform the development and deployment of advanced solutions to the nation's energy challenges.

Goals

To meet its mission, CESD developed this strategic plan to articulate the Division's goals for the period 2018–2023. Central to its mission, CESD investments in basic research address key uncertainties in the understanding of Earth system components, as well as complex uncertainties that arise from the interactions and interdependencies of these components in the coupled Earth system. CESD also makes a special effort to exploit unique DOE facilities and capabilities, thus CESD has greater investments involving atmospheric, terrestrial and computational issues, while also leveraging and coordinating across multiple National Science and Technology Council agencies to achieve CESD goals. Though following the strategy of the previous plan (for the period 2012–2017), the new plan focuses primarily on specific scientific questions requiring an integrated and coordinated approach, as well as the determined effort of multiple CESD programs, projects, and scientific user facilities. In many cases, the new plan leverages strategic interagency partnerships and expertise to achieve major advances in important areas of scientific research. Furthermore, the plan considers scientific needs articulated by DOE's applied energy program offices as complementary to the scientific opportunities articulated by the basic

Earth system research community within DOE's Office of Science.

Scientific Grand Challenges

CESD's strategic plan is framed by five scientific grand challenges focused on collaborative and integrative research across the Division. This research leverages capabilities of BER's scientific, computational, and user facilities as well as other BER community resources to achieve these scientific grand challenges.

1. **Integrated Water Cycle Scientific Grand Challenge.** Advance understanding of the integrated water cycle by studying relevant processes involving the atmospheric, terrestrial, oceanic, and human system components and their interactions and feedbacks across local, regional, and global scales, thereby improving the predictability of the water cycle and reducing associated uncertainties in response to short- and long-term perturbations.

2. **Biogeochemistry Scientific Grand Challenge.** Advance a robust, predictive understanding of coupled biogeochemical processes and cycles across spatial and temporal scales by investigating natural and anthropogenic interactions and feedbacks and their associated uncertainties within Earth and environmental systems.

3. **High Latitudes Scientific Grand Challenge.** Understand and quantify the drivers, interactions, and feedbacks both among the high-latitude components and between the high latitudes and the global system to reduce uncertainties and improve predictive understanding of high-latitude systems and their global impacts.

4. **Drivers and Responses in the Earth System Scientific Grand Challenge.** Advance next-generation understanding of Earth system drivers and their effects on the integrated Earth-energy-human system.

5. **Data-Model Integration Scientific Grand Challenge.** Develop a broad range of interconnected infrastructure capabilities and tools that support the integration and management of models, experiments, and observations across a hierarchy of scales and complexity to address CESD scientific grand challenges.
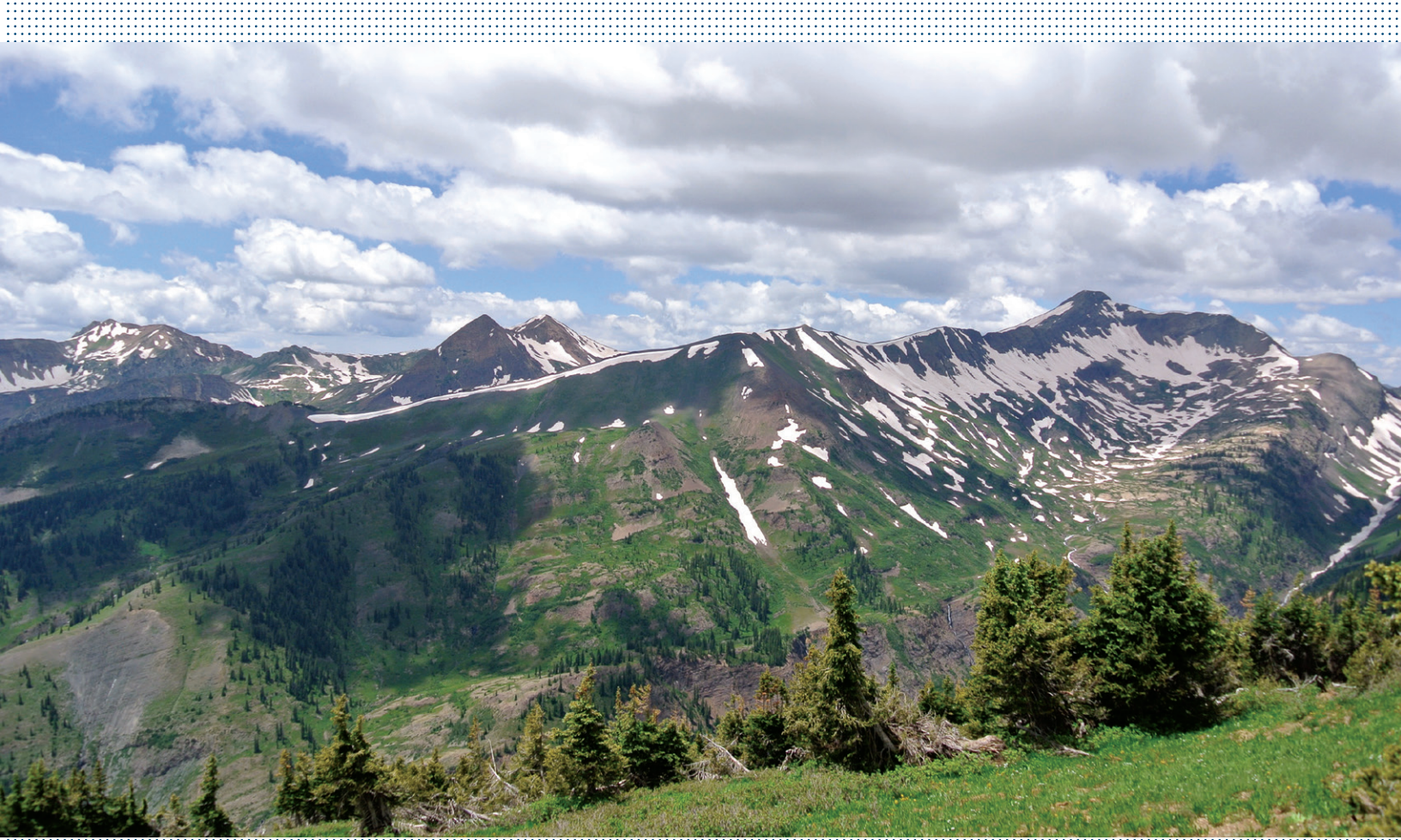
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Mission

Chapter 1
Mission

The mission of the U.S. Department of Energy (DOE) is to enhance the security and economic growth of the United States through transformative science, technology innovation, and market solutions to meet U.S. energy, nuclear, and environmental challenges (U.S. DOE 2014). The first of DOE's four goals focuses on science and energy and seeks to "advance foundational science, innovate energy technologies, and inform data driven policies that enhance U.S. economic growth and job creation, energy security, and environmental quality…." As part of this goal, DOE emphasizes the need for mission-relevant science and technology that can inform the development of energy infrastructure that is secure and resilient to a wide range of environmental and other pressures (U.S. DOE 2014).

Basic science supports the objectives of the first goal of DOE's strategic plan by describing and improving understanding of environmental and other stressors that can introduce risks to infrastructures during their various lifetimes. Basic science also is needed to design and inform prediction tools, so that future technologies can be designed and deployed to ensure that infrastructure (1) provides uninterrupted energy to U.S. stakeholders; (2) is affordable to public- and private-sector entities; and (3) will be resilient to environmental factors such as extreme weather, hydrological changes, and other phenomena over the multidecadal lifetimes of U.S. energy systems.

DOE's Office of Science provides direct support for both fundamental scientific research and for the development, construction, and operation of unique, open-access scientific user facilities. The mission of the Office of Biological and Environmental Research (BER), within the Office of Science, is to support fundamental research and scientific user facilities to achieve a predictive understanding of complex biological and environmental systems for a secure and sustainable energy future. BER research programs seek to understand the governing energy-relevant biological and environmental processes that extend from submicron to global scales, from individual molecules to ecosystems, and from nanosecond to multidecadal time scales. The unique value BER adds in support of the DOE mission is the extension and integration of process-level understanding of complex systems into improved capabilities that, in turn, enhance predictability over a wide range of space and time scales. BER also guides the strategic directions and activities of three DOE scientific user facilities in support of BER

CESD Mission Statement

CESD's mission is to enhance the seasonal to multidecadal predictability of the Earth system by using long-term field experiments, DOE user facilities, modeling and simulation, uncertainty characterization, best-in-class computing, process research, and data analytics and management to inform the development of advanced solutions to the nation's energy challenges.

science [i.e., Atmospheric Radiation Measurement (ARM) User Facility, Environmental Molecular Sciences Laboratory (EMSL), and Joint Genome Institute (JGI)].

The Climate and Environmental Sciences Division (CESD) is one of two BER divisions. CESD's mission is to enhance the seasonal to multidecadal predictability of the "Earth system" by using long-term

field experiments, DOE user facilities, modeling and simulation, uncertainty characterization, best-in-class computing, process research, and data analytics and management (see Fig. 1. Gulf Stream Heat Transport, this page). This mission is dedicated to provide the fundamental science needed to inform development and deployment of advanced solutions to U.S. energy challenges. Within this context, the Earth system includes atmospheric, oceanic, terrestrial, subsurface, cryospheric, and human-energy components. Given

Fig. 1. Gulf Stream Heat Transport. The Gulf Stream transports heat from the tropics to Europe, as shown by surface temperatures in the Model for Prediction Across Scales-Ocean (MPAS-O). The divergent white point highlights the Gulf Stream at 20 °C. Improving the representation of atmospheric, terrestrial, and subsurface processes in Earth system models such as MPAS-O increases the quality of climate model projections and informs DOE's energy decisions. [Courtesy Los Alamos National Laboratory]

> ## Integrated Earth System
>
> The integrated "Earth system" comprises a complex set of interacting physical, chemical, biological, and societal processes that have significant coupling with the climatic and environmental systems.

DOE's mission to adequately assess energy-relevant infrastructure risks, CESD places great emphasis on identifying and quantifying sources of uncertainties across the unified Earth system as a means to extend system understanding and predictability.

This strategic plan addresses CESD's mission and goals for the period 2018–2023, as framed by its five scientific grand challenges. These grand challenges focus on collaborative and integrative research activities across CESD that leverage the capabilities of BER's scientific user facilities, DOE's leadership class computing facilities, and other BER community resources. Central to its mission, CESD investments in basic research address key uncertainties in the understanding of Earth system components, as well as the complex uncertainties that arise from the interactions and interdependencies of these components in the coupled Earth system. This research is needed to understand and predict how
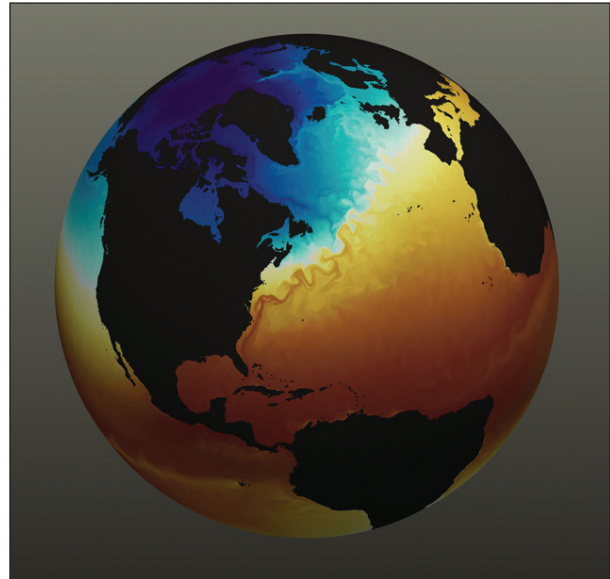
environmental stressors affect and interact with the U.S. energy system and how the combination of natural and human-derived processes lead to variabilities and trends within the integrated Earth system. The scientific questions involving climate and climate change are treated within the context of the Earth system. CESD also addresses DOE's unique concerns regarding wastes from DOE's legacy and ongoing energy and environmental missions. The scope of CESD process research spans scales from molecular to global and durations from nanoseconds to many decades.

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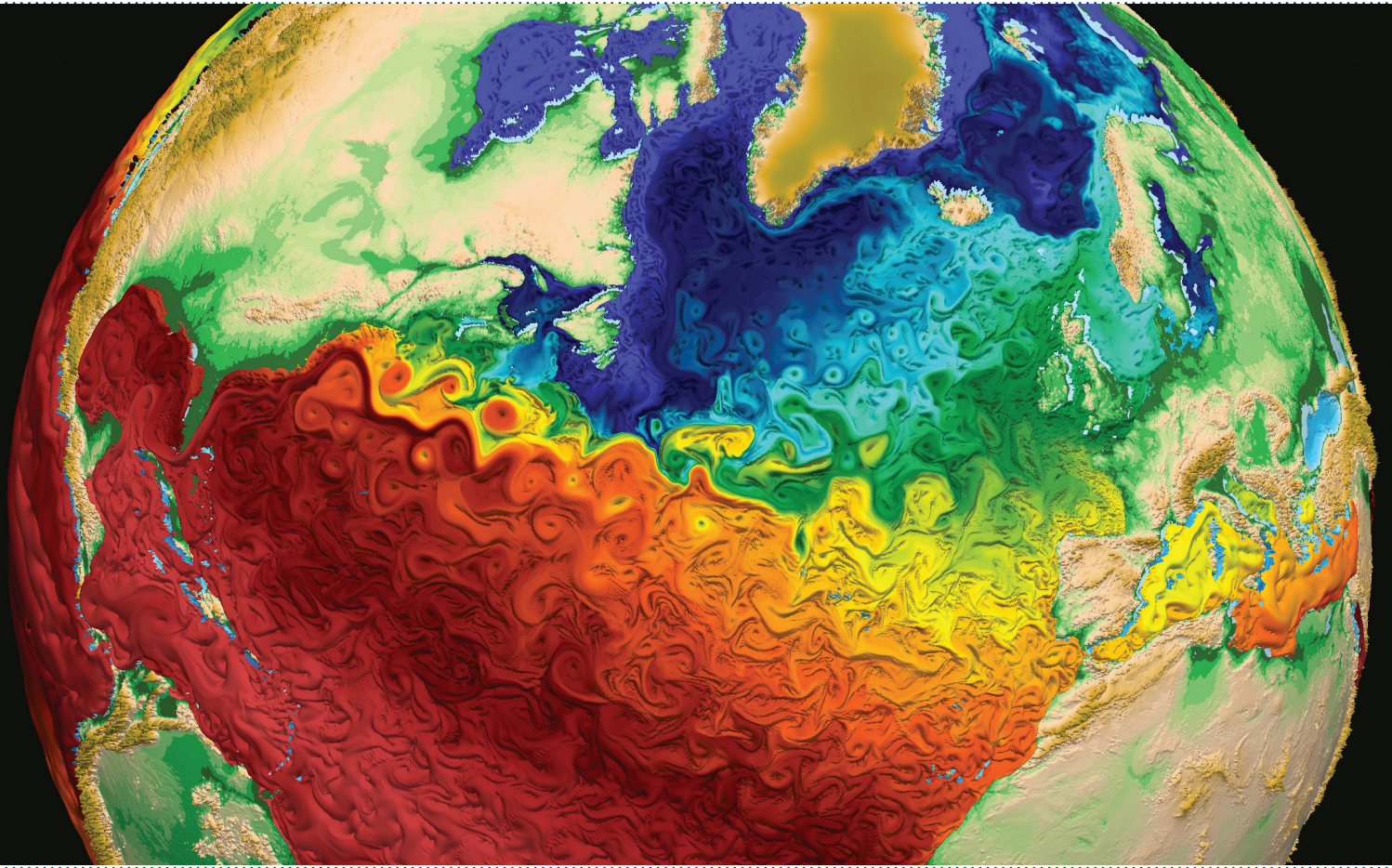
Vision and Values
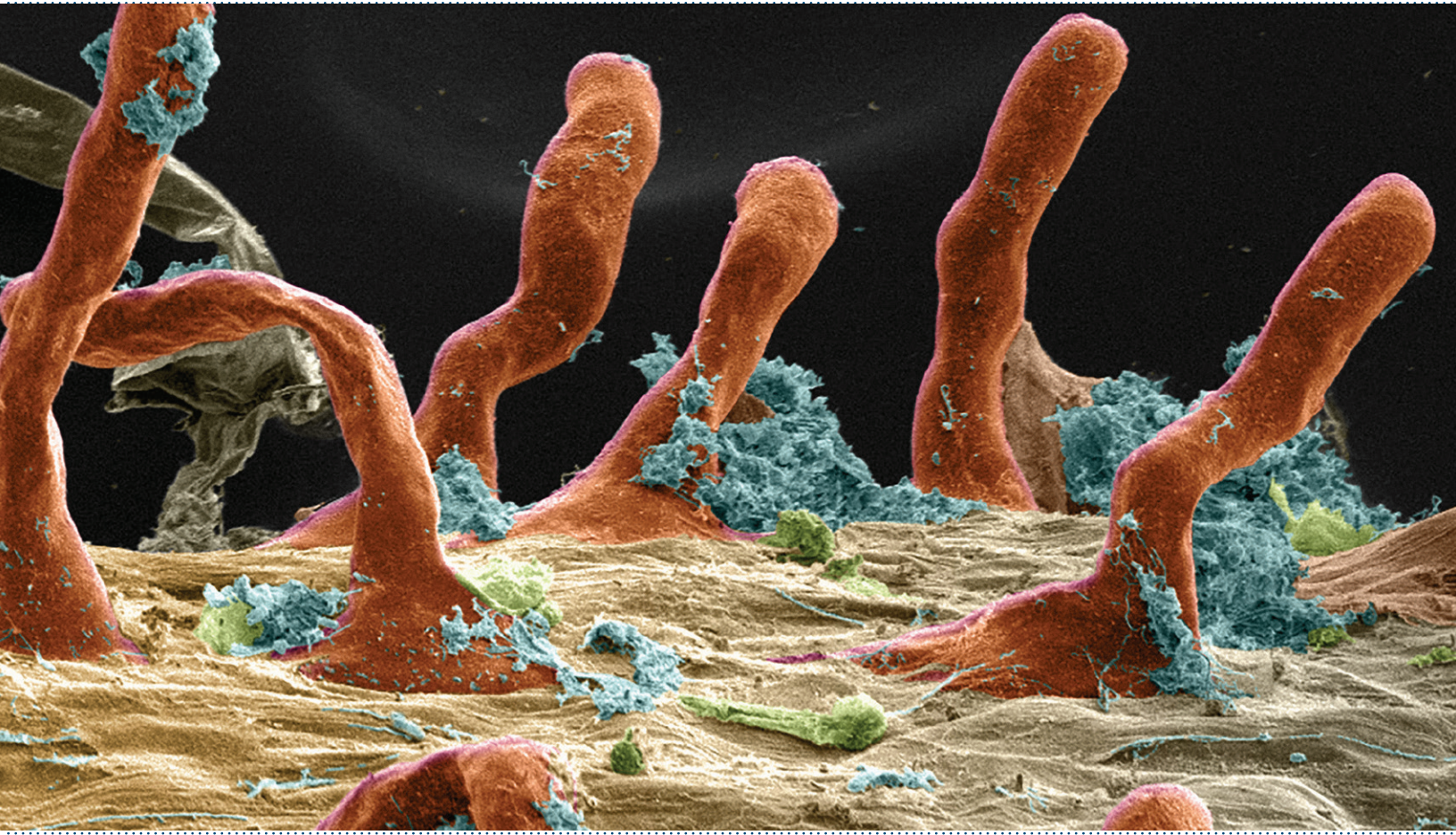
Chapter 2
Vision and Values

Climate and Environmental Sciences Division (CESD) vision: An improved capability for Earth system prediction on seasonal to multidecadal time scales to inform the development of resilient U.S. energy strategies.

The following fundamental values underlie CESD's mission and vision:

- Basic scientific research is the foundation for fueling future innovation and technologies to support the Department of Energy's (DOE) mission.

- A balanced portfolio of basic research includes multi-institutional big science and smaller discovery-focused science projects and takes advantage of the complementary strengths of the DOE national laboratories, DOE user facilities, academic community, and broader scientific community.

- The DOE national laboratories have unique capabilities to conduct integrated, coordinated, and sustained research programs to address innovative and sometimes high-risk transdisciplinary research problems.

- Scientific user facilities, long-term (e.g., decadal) field experiments, community research infrastructure, community databases, advanced Earth system modeling capabilities, and analytical tools enable mission-relevant Earth system science, advance scientific discovery, and broaden the impact of CESD-supported research.

- Developing an effective predictive understanding across the multiple scales of the Earth system requires integrating observational, experimental, analysis, and modeling activities, each informing the others to advance science.

- Effective use of DOE high-performance computational capabilities and advanced mathematical methods is critical to advancing robust, predictive understanding and analysis of uncertainties within the Earth system.

- Effective data management, including developing community data standards and formats and sharing and preserving data, will increase the pace of scientific discovery and ensure scientific integrity.

- Engagement with the broader U.S. and international scientific research community and coordination with intra- and interagency partners, including the National Science and Technology Council and its subcommittees, create synergies of activities, capabilities, and tools that accelerate the pace and impact of scientific discovery.

- Essential context, relevance, value, and quality of CESD research and facility activities are ensured through community engagement that includes peer reviews and DOE-sponsored workshops.

- Coordination and regular interaction with appropriate applied activities within DOE ensure appropriate alignment of CESD research activities with the needs of DOE's applied energy mission.

- Development of cutting-edge capabilities, expertise, and scientific leadership is fostered through investments in early-career research and technology-development opportunities.

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Plan Background and Purpose

Chapter 3
Plan Background and Purpose

3.1 Background

From 2010 to 2011, the Climate and Environmental Sciences Division (CESD) developed a strategic plan that would frame the Division's high-level research priorities over the next 5 years (2012–2017). The *Climate and Environmental Sciences Division Strategic Plan* was released and published in 2012 (U.S. DOE 2012). As part of that plan, CESD described a Department of Energy (DOE) mission–relevant science strategy to support creative and innovative basic research investments that focused on a vision to improve predictability of climate and environmental systems. With implementation of the 2012 plan, CESD adopted a systems approach that considered both DOE applied mission science needs and scientific sources of major uncertainty that needed to be reduced or resolved. Relations were built with federal offices engaged in electrical grid reliability, renewable energy, and environmental remediation.

Since publication of the 2012 strategic plan, new and ongoing major CESD investments and activities have shaped CESD's evolving long-term vision to enhance Earth system predictability. Examples of big science research investments during 2012 to 2017 that were led by national laboratories included (1) major terrestrial field projects involving permafrost ecology, tropical ecology, and geomorphology; (2) the launch of a comprehensive Earth system model (ESM) project designed to run efficiently on DOE high-performance computers; (3) polar research involving the dynamical modeling of sea ice, ice sheets, and ocean-atmosphere-land interactions; (4) above- and belowground biogeochemistry research exploiting new experimental manipulation studies in northern peatland ecosystems; (5) watershed-scale studies involving hydrobiogeochemistry;

(6) advanced cloud and aerosol observations using experiment, modeling, and simulation; (7) simulation and analysis of extreme events as part of a dynamic climatic, hydrological, and Earth system; (8) novel software and adaptive mesh technologies for system modeling; (9) benchmark analysis and uncertainty quantification; and (10) new attention to data management and cyberinfrastructure. CESD further embraced its approach of coupling experiments and modeling under the integrated "model-observation-experiment (ModEx) paradigm" (see Fig. 2, p. 9).

During the past 5 years, CESD increasingly supported research dedicated to integrating and coupling of various Earth system components, where both atmospheric and oceanic modeling efforts began to incorporate nonhydrostatic physics and terrestrial ecology research activities incorporated trait-based approaches and other new methodologies. Workshops also were conducted to promote joint strategies between facilities and science programs that, in turn, were translated into interdisciplinary and multidisciplinary funding opportunities. During the same period, the modeling of these integrated systems increasingly incorporated impacts, adaptation, and vulnerability as complements to integrated assessment to more appropriately address how extreme phenomena interact with all system components. Key collaborations with other agencies also were fostered, most notably with the National Science Foundation (NSF), National Oceanic and Atmospheric Administration (NOAA), National Aeronautics and Space Administration (NASA), U.S. Geological Survey (USGS), U.S. Department of Agriculture (USDA), and Office of Naval Research (ONR).

Given the fine spatial and temporal scales that are necessary to advance predictability of modeling systems,
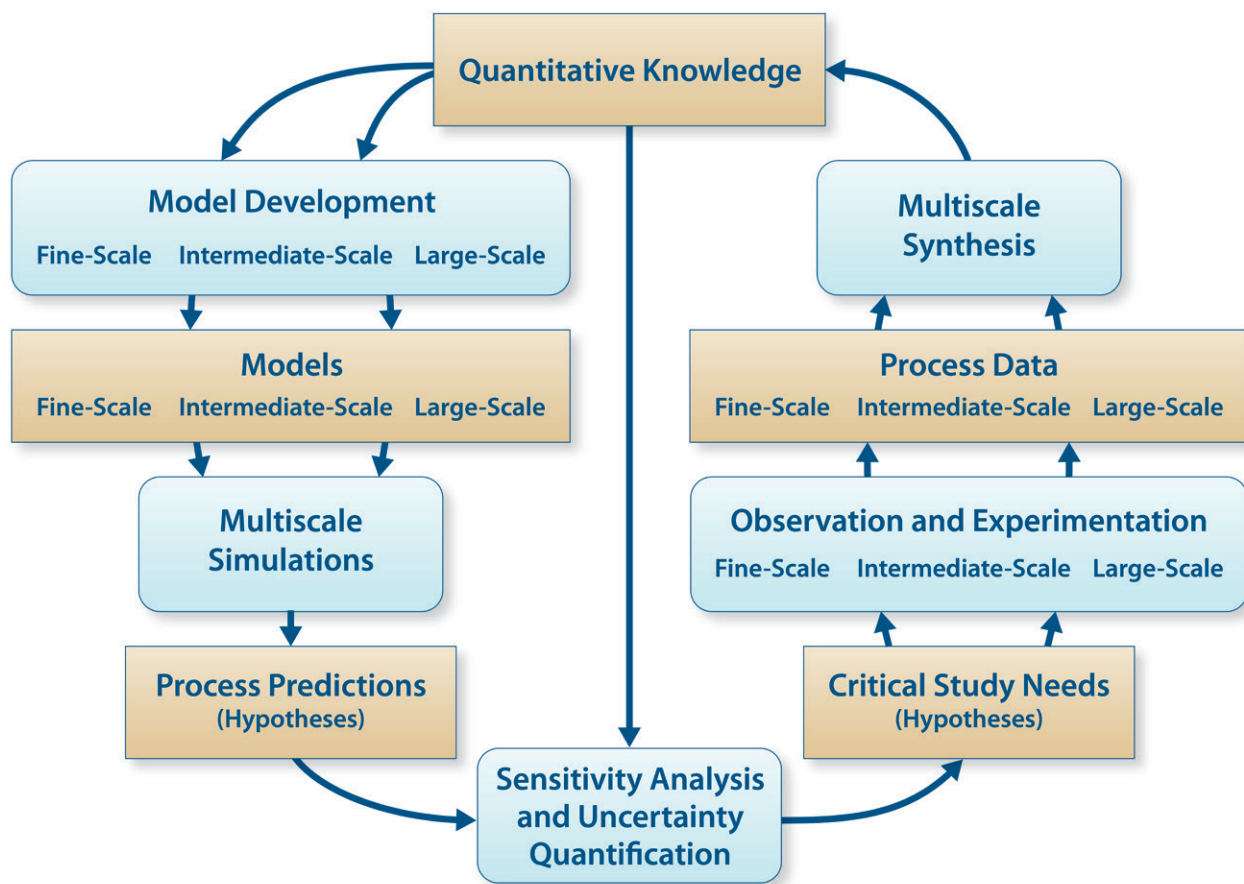
Fig. 2. Integrated Model-Observation-Experiment (ModEx) Paradigm. CESD's ModEx approach integrates process research, which involves observations, experiments, and measurements performed in the field or laboratory, with modeling research, which simulates these same processes. This integrated loop ensures that models incorporate state-of-the-science knowledge about critical systems, and the resulting improved models can be used to guide field and laboratory research to inform future decisions.

CESD partnered with DOE's Office of Advanced Scientific Computing Research (ASCR) in developing strategies to exploit advanced software and hardware as part of the "DOE exascale strategy." At the finer spatial and temporal modeling scales, other opportunities and priorities arose within DOE that were clear beneficiaries of CESD's unique capabilities. These included, for example, the improved capability to predict extremes in temperatures and storms that, in turn, affect the likelihood of blackouts and cascading failure of connected infrastructures.

With a growing interest in integrated hydrological interactions within the Earth system and recent droughts in the western United States that impact U.S. energy systems, CESD expanded its priorities to understand the predictability of the water cycle to inform understanding of future water supplies. These energy-relevant needs further motivated CESD's evolution to an Earth system–centric focus.

By treating its investments within an Earth system context, CESD became better positioned to interact

with a broader set of stakeholders who require basic science research to address novel questions that demand new CESD science and better prediction capabilities. For example, questions within DOE over the past few years have increasingly focused on how variability and change within the Arctic region affect energy production and pipeline security; how interannual variability of water supplies affects terrestrial oil and gas recovery; and how extremes within the Earth system affect energy production and electric grid reliability. The science needed to improve Earth system predictability to address these broader questions was considered in developing a revised set of scientific grand challenges for CESD's strategy spanning 2018 through 2023 (see Chapter 4. CESD Scientific Grand Challenges for 2018–2023, p. 12).

In November 2017, the Biological and Environmental Research Advisory Committee (BERAC) released a major report, *Grand Challenges for Biological and Environmental Research: Progress and Future Vision* (BERAC 2017). BERAC suggested in the report that CESD consider including in its future strategic investments the development of enhanced Earth system modeling capabilities that focus on extreme events, data-model integration, uncertainty quantification, and the DOE exascale agenda; a computational user facility to help drive model development and analysis; and deployment of integrated field laboratories that incorporate newly developed sensing technologies and address environments such as urban areas and their surrounding ecosystems. While the BERAC report emphasized challenges extending over a 20-year period (i.e., 2017–2037), CESD incorporates in its 5-year (2018–2023) strategic plan those BERAC recommendations as a framework for the Division's near-term challenges and priorities.

Moving forward, CESD's use-inspired basic research will target new science that demands more sophisticated DOE facilities and capabilities. Meeting this new plan's objectives will enable revolutionary scientific advances that are expected to more effectively inform DOE's evolving priorities in energy-sector resiliency and security.

3.2 The CESD 2018–2023 Strategic Plan

The CESD strategic plan for the period 2018–2023 presents a bold set of high-priority CESD grand challenge fundamental scientific research questions that are critical to DOE's science, environmental, and energy missions and that CESD is particularly well positioned to address. While noting that CESD research is dedicated to long-term scientific challenges, potentially extending across multiple decades, this plan focuses on the specific scientific questions and priorities needed to improve Earth system predictability over the coming 5 to 10 years. As in the previous strategic plan, the grand challenges of this new plan require an integrated and coordinated approach, as well as the determined effort of multiple CESD programs, projects, and scientific user facilities, and, in many cases, leveraging strategic interagency and stakeholder partnerships and expertise. The new plan places greater emphasis on DOE scientific needs, yet its approach is framed by science opportunities and directions articulated by the research community. As in its previous plan, CESD will emphasize the use of DOE's unique facilities and infrastructures.

The plan's five scientific grand challenges span cutting-edge research within water-cycle, biogeochemistry, and high-latitude processes; drivers and responses in the Earth system; and the development of advanced data-model integration frameworks for enhancing scientific discovery. In each case, major scientific advances will serve and inform the needs of DOE's mission (see Chapter 4, p. 12).

Following presentation of the research challenges, this report provides descriptions of relevant CESD activities and facilities that highlight the Division's scope, approaches, expertise, and efforts (see Appendix 1, p. 26). Also described are ongoing high-priority CESD investments that are more confined to individual programmatic disciplinary areas such as atmospheric research, environmental and terrestrial research, and Earth system modeling.

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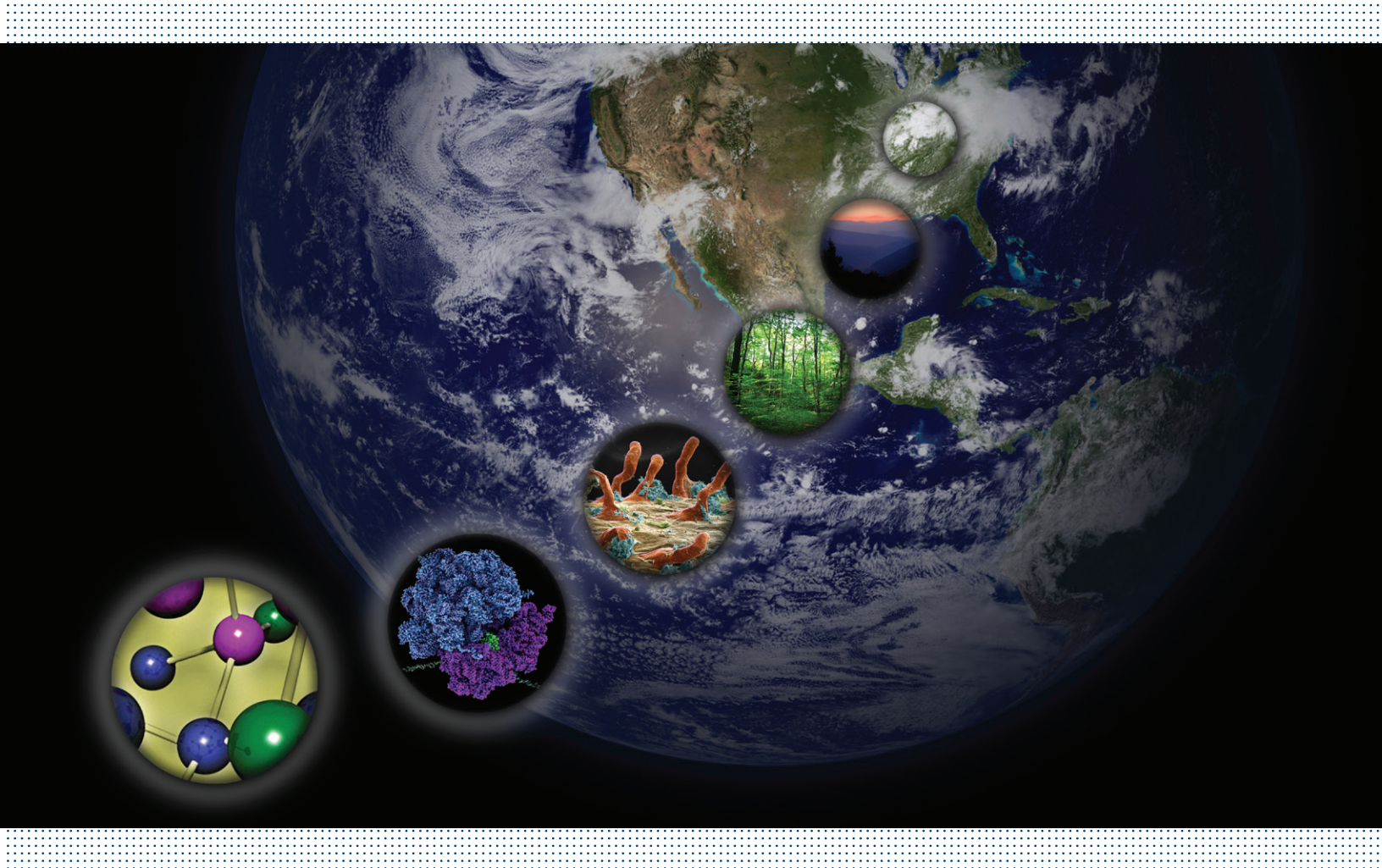
CESD Scientific
Grand Challenges for 2018–2023

Chapter 4
CESD Scientific Grand Challenges for 2018–2023

4.1 Integrated Water Cycle Scientific Grand Challenge

Advance understanding of the integrated water cycle by studying relevant processes involving the atmospheric, terrestrial, oceanic, and human system components and their interactions and feedbacks across local, regional, and global scales, thereby improving the predictability of the water cycle and reducing associated uncertainties in response to short- and long-term perturbations.

Associated Research Questions

1. How are the frequency and intensity of hydrological events affected by coupled, large-scale variability and change within the Earth system?

2. How are atmospheric moisture; cloud formation and properties; and the location, quantity, and phase of precipitation at regional to local scales influenced by atmospheric and surface processes across a range of scales including large-scale atmospheric motions, land-atmosphere coupling, heat and moisture transport, cloud-aerosol-precipitation interactions, and turbulence processes?

3. How does the hydrological functioning of watersheds and river basins, including natural, managed, and engineered components, respond to changes in precipitation patterns, land use, vegetation cover, geomorphology, nutrient and contaminant loading, and compounding disturbances?

4. How do energy, water, and land systems, which are inextricably linked across local and regional scales,

co-evolve in response to short- and long-term perturbations?

5. To what extent do local-scale heterogeneities and anomalies, including both natural and anthropogenic system components, drive larger-scale hydrological processes and phenomena, and how persistent and predictable are these interactions?

Water is essential for a wide range of life-sustaining human activities and is a major component underlying a suite of important Earth system processes and interactions that extend from local to regional to global scales. The integrated water or hydrological cycle involves the hydrology and movement of water among ocean, atmosphere, land, and cryosphere, as well as the interactions of these components with human activities including withdrawals, consumption, and diversion. Many energy systems such as fossil, nuclear, and hydroelectric power plants depend on water availability, as does the growth of biofuels. Improved understanding of the processes underlying the integrated hydrological cycle is critical for improving the predictability of water availability and quality for energy infrastructure needs and the potential impacts of extreme hydrological events on energy infrastructure and the environment (see Fig. 3. East River Watershed in Upper Colorado River Basin, p. 13). A combination of natural variability and human activities affects the hydrological cycle, including uses of water for agriculture and energy production. Today's scientific uncertainties in predicting long-term changes in global and regional hydrological cycles and the implications for water supplies and energy production (from local to regional scales) fundamentally limit the nation's ability

Fig. 3. East River Watershed in Upper Colorado River Basin. At this representative watershed, studies supported by the Subsurface Biogeochemical Research activity in the Environmental System Science research area are developing and testing new approaches and tools to measure and predict how droughts, early snowmelt, and other perturbations impact downstream water availability and biogeochemical cycling at episodic to decadal time scales. [Courtesy Lawrence Berkeley National Laboratory]

to develop sustainable energy solutions and address environmental needs.

To advance a robust, predictive understanding of the integrated water cycle, the Climate and Environmental Sciences Division (CESD) draws from unique and highly relevant research on cloud, aerosol, terrestrial-ecosystem, watershed, and subsurface processes, as well as from integrated energy-Earth system modeling across a variety of spatial and temporal scales. Synthesizing new process knowledge and innovative computational methods in integrated models of the human-Earth system can advance predictive capabilities relevant to Department of Energy (DOE) missions (see Fig. 4. Balancing Global Water Availability and Use at the Basin Scale, p. 14).

CESD fundamental research on the integrated water cycle extends from local to global scales. From a global perspective, a major goal is to better understand how the hydrological cycle will evolve on seasonal to multidecadal time scales relevant to energy infrastructure. From a local perspective, major goals include better

understanding of (1) processes that control the details of precipitation location, type, and intensity and (2) how terrestrial-aquatic interfaces, watersheds, and river basins function as fully coupled systems in response to perturbations and other stresses on scales extending from individual storm or flood events to long-term droughts. A hierarchy of models with varying degrees of resolution and mechanistic fidelity must be used to represent the functioning of hydrological systems from local to global scales. Long-term observations, field experiments, and laboratory experiments provide a foundational basis for evaluating and improving the representation of physical processes in the model simulations. Ultimately, this process-based understanding of the natural and human components of the integrated water cycle is incorporated into complex system models that enable hypothesis testing for scientific inquiry and decision support to advance DOE's energy and environmental missions.

4.2 Biogeochemistry Scientific Grand Challenge

Advance a robust, predictive understanding of coupled biogeochemical processes and cycles across spatial and temporal scales by investigating natural and anthropogenic interactions and feedbacks and their associated uncertainties within Earth and environmental systems.

Associated Research Questions

1. How can biogeochemical pools and fluxes and their associated uncertainties be better constrained and represented in environmental and Earth system models at global to local scales?

2. How can improved understanding of biogeochemical interactions and feedbacks within the current Earth system be used to improve projections of future environmental states?

3. How will compounding short-term perturbations and sustained change influence biogeochemical cycles and impact the functioning of Earth and environmental systems across relevant spatiotemporal scales, and what are the associated critical thresholds of those systems?

Fig. 4. Balancing Global Water Availability and Use at the Basin Scale. Advanced simulation capabilities, enabled through the Multisector Dynamics activity in the Earth and Environmental Systems Modeling research area, are revealing new insights into the integrated water cycle, including regional water resources and demands as well as global projections oriented around major river basins. [Courtesy iStockphoto.com]

4. How do natural and anthropogenic changes in land cover and land use affect biogeochemical processes and cycles, especially at critical land-water-atmosphere interfaces?

5. How do geochemical, genomic, and metabolic interactions influence environmental system dynamics from single-measurement sites to watershed scales, and how can improved understanding of these processes and interactions be effectively incorporated into environmental and Earth system models?

6. What are the key environmental factors that create and sustain biogeochemical "hot spots" and "hot moments" in specific locations, and to what extent are these phenomena important at larger scales?

Advancing the understanding of coupled biogeochemical processes and cycles enables DOE to address a wide variety of mission needs. These needs include the representation and long-term prediction of the Earth system, understanding the complexities of the energy-water-land nexus, and understanding of nutrient availability in soils for sustainable biofuel crops. Additionally, understanding and predicting the cycling and transport of nutrients and DOE-relevant contaminants in surface water, soils, and the subsurface, as well as analyzing science-based approaches for handling spent nuclear fuel storage, are

critical science needs for DOE. Developing a foundational understanding of the transformation, pools (stocks), and fluxes (movement) of biogeochemical elements in terrestrial and subsurface environments and their coupling with hydrology will reduce key uncertainties in Earth and environmental sciences that have implications for the environment and U.S. energy systems (see Fig. 5. Carbon and Nutrient Cycling, p. 15). Because most DOE mission areas involve human interactions with the natural Earth system, there also is a need to integrate research to understand natural biogeochemical processes and cycles with research to study the influence of anthropogenic activities. Achieving this integration requires (1) field-based observational and experimental research as well as laboratory-based research on real-world systems and (2) incorporation of the findings and understanding from these research activities into a variety of process and predictive models that span a wide range of spatial and temporal scales.

Model complexity needs to be tailored to particular scales and questions. However, current land-process, terrestrial-ecosystem, watershed, and reactive-transport models inadequately capture the structure of the land surface, coastal oceans, freshwater systems, soils, groundwater, deeper sediments, and their interfaces. These models also do not adequately represent living components of the Earth system such as microbes, plants, and higher organisms. Finally, they insufficiently represent the interfaces and interactions among the physical, chemical, and biological processes that compose the interconnected Earth system.

Functional processes of the Earth system include (1) emissions of biogenic aerosol precursors from soils and waterbodies; (2) biogeochemical reactions in soils and aquatic sediments, such as contaminant transformations; (3) interactions and cycling of organic and inorganic elements such as carbon, nitrogen, iron, sulfur, phosphorous, and many others through the bio- and geosphere; (4) plant-microbe interactions in rhizospheric reduction-oxidation (redox) reactions in aquifers and soil pores; (5) reactive transport of particulates, organic matter, microbes, and contaminants; (6) microbe-mineral interactions; and (7) hot spots

Fig. 5. Carbon and Nutrient Cycling. Coarse roots, such as this root mass from a soil core taken in a scrub-oak forest, often persist for long periods after tree harvest or disturbances such as fire. Research supported by the Terrestrial Ecosystem Science activity in the Environmental System Science research area applied ground-penetrating radar to image belowground plant structures to help quantify belowground carbon pools. [Courtesy Frank Day, Old Dominion University]

and hot moments of disproportionately high levels of hydrobiogeochemical interactions relative to the bulk of the environment (see Fig. 6. Biogeochemical Hot Moments, p. 16). To enable a robust understanding of Earth system functions and prediction of major changes to the Earth and relevant environmental systems following perturbations or even major disturbances, these and many other biogeochemical processes need to be more completely investigated and understood at their appropriate scales.

4.3 High Latitudes Scientific Grand Challenge

Understand and quantify the drivers, interactions, and feedbacks both among the high-latitude components and between the high latitudes and the global system to reduce uncertainties and improve predictive understanding of high-latitude systems and their global impacts.

Associated Research Questions

1. How will the surface energy budget be impacted by changes in high-latitude atmospheric vertical structure, aerosols, clouds, and their interactions under current and future conditions?

2. What are the critical coupled high-latitude biogeochemical processes at local scales that have implications for the global Earth system, and how will these coupled cycles be impacted by current and future high-latitude changes and disturbances?

3. How will the polar cryosphere change under a range of potential future conditions; how does this compare to historical changes; and what are the relevant primary processes, drivers, and feedbacks within the Earth system?

4. To what extent are changes in high-latitude regions driven by local versus global influences, and what are the impacts of high-latitude change on lower-latitude systems through, for example, shifts in large-scale circulations?

5. What are the uncertainties in high latitude–driven global sea level–rise projections, and what are the associated coastal impacts, especially when combined with extreme events and other compounding factors?

The largest observed changes in the Earth system are happening in high-latitude regions. The Arctic is experiencing very dramatic changes related to thawing permafrost, melting sea and land ice, and warming oceans. The retreating sea-ice cover in the Arctic and warmer temperatures are opening up opportunities for energy exploration and shipping. For the Antarctic, several ice shelves are particularly susceptible to thinning by underlying warm ocean currents, possibly leading to ice-sheet destabilization and sea-level rise (see Fig. 7. Modeled Ice Speed for the Antarctic Ice Sheet, p. 17). The healing of the Antarctic ozone hole affects the Southern Hemisphere's atmospheric and oceanic dynamics. In addition, changes in the high latitudes of both the Arctic and Antarctic affect the entire planet through shifts in atmospheric and oceanic circulations. Both the desire for energy security and the need to better understand the influence of high-latitude changes on midlatitude weather and climate (e.g., in the continental United

Fig. 6. Biogeochemical Hot Moments. Researchers install *in situ*, permeable solid phase-groundwater reaction cells into wells at DOE's Rifle, Colorado, field site to investigate molecular-scale mechanisms governing uranium mobility in response to seasonally changing groundwater conditions. This work is supported by the Subsurface Biogeochemical Research activity in the Environmental System Science research area. [Courtesy SLAC National Accelerator Laboratory]

States) highlight the paramount need to understand the sensitivities, interactions, and feedbacks, both within and between the individual components (e.g., atmosphere, oceans, cryosphere, and land) of the Arctic and Antarctic systems and between these regions and the rest of the planet.

Although progress has been made in understanding high-latitude systems both at a component level and a comprehensive system level, scientific advances in the predictability of high-latitude systems have been and still are impeded by several factors. These factors include sparsity of observations, lack of process knowledge and simulation of individual components and their interactions, the multiscale nature of processes, and the lack of resolution in global and regional Earth system models (ESMs) in capturing the relevant processes and their interactions. In addition, unique aspects of high-latitude systems continue to limit the ability to predict high-latitude variability and change. Specifically, the largest interannual variability of the Earth system is found in high-latitude regions, yet

observing and simulating high-latitude processes remain extremely challenging, especially when considering permafrost thaw and changing landscape morphology that complicate land-model development (see Fig. 8. Landscapes in Transition, p. 18). Furthermore, cryospheric and biogeochemical processes are highly complex at high-latitude system interfaces between, for example, land ice and ocean, land ice and atmosphere, and land and ocean.

With unique atmospheric and terrestrial observational investments in the high latitudes and complementary internationally recognized sea-ice, land-ice, terrestrial, atmospheric, and oceanic modeling and analysis capabilities, CESD is uniquely poised to make advances in the understanding of high-latitude systems and their feedbacks. To address scientific challenges involving high latitudes, CESD seeks to strengthen and coordinate its terrestrial, atmospheric, and modeling foci and increase interactions with other U.S. agencies and international partners. CESD's terrestrial priority over the next 5 years will focus, more specifically, on understanding the evolving ecological, physical, and biogeochemical interactions in permafrost and boreal systems with increased emphasis on interactions with hydrology and the atmosphere. The focus on atmospheric processes will be to enhance understanding of changes within high-latitude systems, with specific efforts to improve knowledge of surface-atmosphere interactions, microphysics of mixed-phase clouds, and the impacts of long-range transport versus local production of absorbing aerosols as needed to project surface radiation budgets (see Fig. 9. Tethersonde Test Flight, p. 18). Implementing the new process knowledge into ESMs with regionally refined gridding capabilities for terrestrial, oceanic, and atmospheric components is expected to enable a sharper focus on regional-scale interactions, thereby reducing the model computational cost required to capture essential Earth system behavior while resolving high-latitude processes that have a global impact. Sensitivity analysis performed using ESMs will lead to better understanding of relevant drivers, interactions, and feedbacks and will help identify the
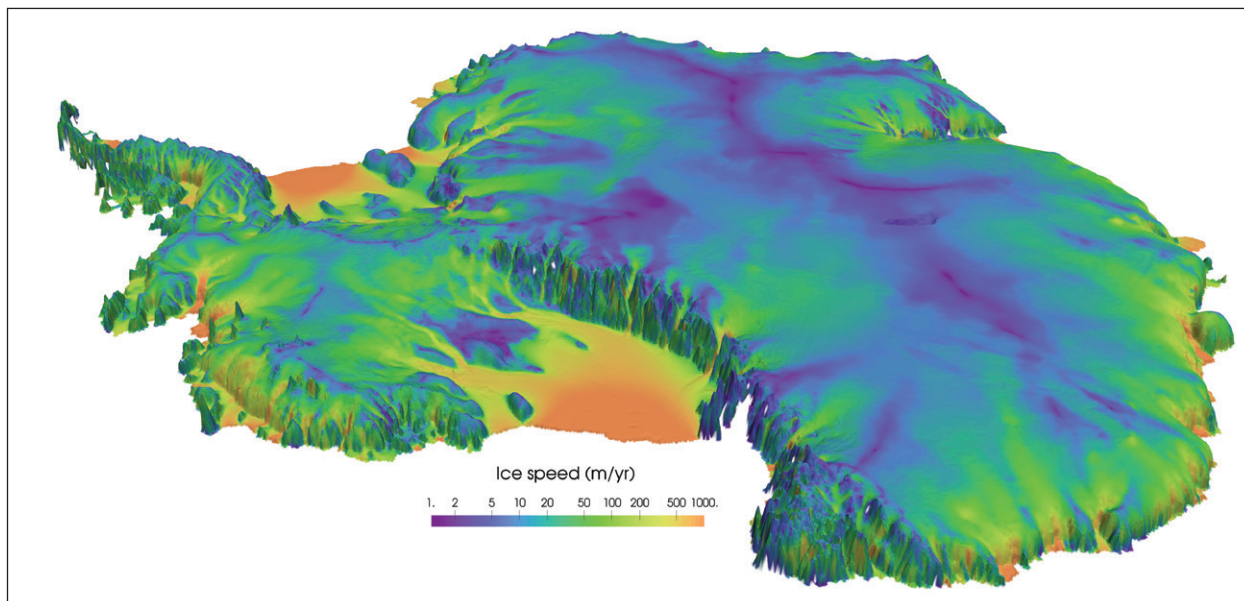
Fig. 7. Modeled Ice Speed for the Antarctic Ice Sheet. Slow-moving ice (blue and green) from the ice sheet's interior feeds fast-moving (yellow and orange) ice streams and ice shelves that ring the continent's margins. These margins restrain the vast body of ice behind them but are susceptible to speed up and destabilization through melting from the ocean below and atmosphere above. The Model for Prediction Across Scales (MPAS)-Albany Land Ice model used for this simulation is supported by the Model Development activity in the Earth and Environmental Systems Modeling research area. [Courtesy Los Alamos National Laboratory]

next set of observations needed to further reduce the uncertainties in Earth system projections.

4.4 Drivers and Responses in the Earth System Scientific Grand Challenge

Advance next-generation understanding of Earth system drivers and their effects on the integrated Earth-energy-human system.

Associated Research Questions

1. How do natural and anthropogenic short- and long-lived drivers of the Earth system, such as atmospheric aerosols and gases, clouds, land use, land cover, oceanic circulations, sea ice, and ice sheets, currently interact with the coupled Earth system, and how accurately can future interactions be predicted?

2. How do timing, intensity, and location of drivers interact with natural variability, and how do these affect extremes and potential tipping points across local, regional, and global scales?

3. How do the hydrological cycle, biogeochemical cycle, and high-latitude regions respond to specific natural and anthropogenic drivers?

4. How may the responses of the integrated Earth system influence the accessibility, availability, location, distribution, and usage of U.S. energy supplies and connected infrastructure, as well as critical interdependencies among the energy, water, and land systems?

Understanding the processes and constituents that drive the Earth's different meteorological regimes, as well as the accompanying dynamics within the integrated human-natural Earth system, is key to predicting Earth system responses to these drivers and the subsequent
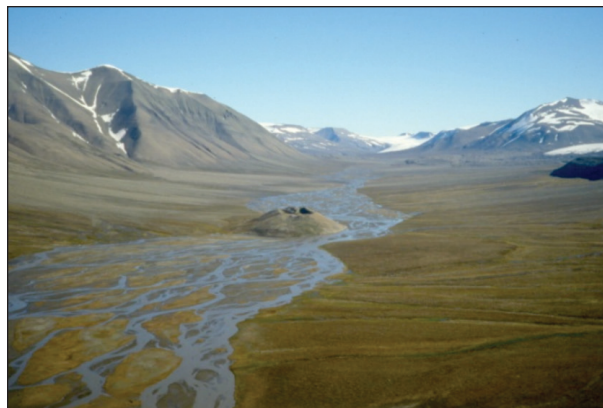
Fig. 8. Landscapes in Transition. A mechanistic understanding of what controls the coupled nature of hydrology, biogeochemistry, and vegetation dynamics is needed for system-wide prediction of permafrost dynamics. The Next-Generation Ecosystem Experiments–Arctic project, supported by the Terrestrial Ecosystem Science activity in the Environmental System Science research area, seeks to understand how surface and subsurface processes and properties are interconnected across permafrost-dominated tundra ecosystems. [Courtesy University of Alaska, Fairbanks]

implications for the energy sector. These drivers span a range of spatial scales, from phenomena the size of a forest fire or volcanic plume to the global scale of atmospheric waves and oceanic currents, and temporal scales from hours to decades. The multiscale nature of these drivers is complicated by the fact that the Earth system has teleconnections—changes in one part of the Earth system in one location can impact other parts of the system in other locations. Further complications include the interactions between human activities and Earth system natural variability and trends. Additionally, many interactions within the Earth system are nonlinear, so changes in timing, intensity, or location of a driver may interact in unexpected ways with natural variability and trends to produce extreme events (see Fig. 10. Sea Surface Temperature Change, p. 19).

A major challenge facing the science community is to understand the relative importance of local versus large-scale dynamics, as well as natural versus continuously evolving anthropogenic systems and drivers of scale-dependent meteorological, climatic, and other system phenomena. One example is the need to improve understanding of the extent to which spatial and temporal changes to the hydrological system, such as seasonal to decadal changes in precipitation and water availability in particular regions, are influenced by local versus large-scale phenomena. Local phenomena include atmospheric particles such as atmospheric particulates, as well as terrestrial influences such as changes in land use, water withdrawals, and water diversion (see Fig. 11. Land-Atmosphere-Cloud Interactions, p. 20). Large-scale phenomena include natural cycles of variability in the Earth system such as the El Niño–Southern Oscillation. Resulting changes in local meteorology or hydrology can impact human communities, including demands on and availability of energy systems. Incorporating all these drivers and responses within integrated ESMs not only improves the potential understanding of the interdependencies of systems, but also leads to understanding how the Earth, energy, and human systems may respond and co-evolve based on component interdependencies.

Responses of the Earth system to drivers impact all of CESD's scientific grand challenges, and addressing this particular grand challenge requires that DOE capabilities and infrastructures be readily available to the community. Specifically, CESD will prioritize research objectives to (1) observe atmospheric, hydrological,

Fig. 9. Tethersonde Test Flight. Tethersondes, like this one, are used to collect atmospheric measurements at the Atmospheric Radiation Measurement (ARM) User Facility's mobile observatory at Oliktok Point, Alaska. [Courtesy ARM User Facility]

and terrestrial systems over sufficient time and space to record fluctuations in both drivers and major Earth system dynamics; (2) implement these component systems into models of various scales to study processes, feedbacks, and responses; and (3) perform modeling and statistical analysis to isolate the roles of drivers in producing responses at various levels within the integrated system hierarchy. The latter is essential for understanding nonlinear characteristics within the integrated Earth system.

4.5 Data-Model Integration Scientific Grand Challenge

Develop a broad range of interconnected infrastructure capabilities and tools that support the integration and management of models, experiments, and observations across a hierarchy of scales and complexity to address CESD scientific grand challenges.

Associated Research Goals

1. Provide an advanced and innovative cyberinfrastructure for archiving, managing, analyzing, and visualizing experimental, observational, and model data (and their associated metadata) that enables scientists to integrate CESD-generated data across projects, scales, and disciplines to address CESD's scientific grand challenges.

2. Develop and use innovative computational tools, testbeds, benchmarks, diagnostics, and metrics, as well as data at process and global scales, to evaluate and validate models and to characterize and understand sources of uncertainty in both observations and model simulations.

3. Enhance efforts to ensure that the results of experiments and observations are used to inform model development and, conversely, that model outputs and simulations are used to guide the design of field experiments and new observational efforts to address critical knowledge gaps.

4. Develop a scalable and adaptable framework that enables improved compatibility, integration, and interoperability of a hierarchical suite of models
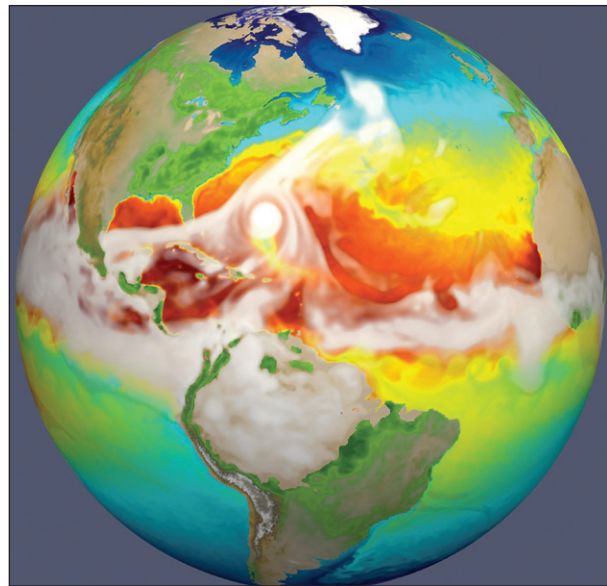

Fig. 10. Sea Surface Temperature Change. The high-resolution Energy Exascale Earth System Model (E3SM) simulates the strongest storms with surface winds exceeding 150 miles per hour, such as hurricanes that leave cold wakes 2–4 °C cooler than their surrounding waters. This simulation represents how sea surface temperature changes evolve as a hurricane (seen here approaching the U.S. East Coast) moves across the Atlantic and how the resultant cold wake affects subsequent intensification of the next hurricane. [Courtesy Los Alamos National Laboratory]

across a range of temporal and spatial scales and complexity to address CESD's scientific grand challenges.

A modern and effective cyberinfrastructure for archiving, managing, analyzing, and visualizing experimental, observational, and model-generated data is critical for supporting scientific investigation of Earth system processes. Such a cyberinfrastructure will enable CESD to strategically manage the large volumes and diversity of data from CESD-supported user facilities, community capabilities, measurement sites, field campaigns, and individual experiments. Leveraging CESD's existing data infrastructure, developing enhanced open-source software and capabilities for incorporating observational and experimental data into CESD-supported models, and making effective use of DOE's high-performance computing facilities

Fig. 11. Land-Atmosphere-Cloud Interactions. The Integrated Cloud, Land-Surface, and Aerosol System Study (ICLASS), supported by the Atmospheric System Research activity, relies heavily on observational datasets being collected at the Atmospheric Radiation Measurement (ARM) User Facility's Southern Great Plains site. This project is designed to understand and model key interactions among clouds, aerosols, and the land surface. [Courtesy ARM User Facility]

will better equip the scientific community to address CESD's scientific grand challenges and enable breakthroughs at the frontiers of Earth system science.

The data needed for effective Earth system research to better understand climatic and environmental variabilities and change over multiple scales continue to increase, both in volume and complexity. To effectively use and steward this information, strong data management practices including quality control, uncertainty characterization, comprehensive metadata, standardization, and discoverability are critical. Scalable open-source software for advanced analysis techniques such as data mining, machine learning, pattern scaling, and visualization will enable scientific discovery. Advanced workflows will enable the reproducibility of research results and simulations and the ability to easily apply new techniques to existing datasets. Digital object identifiers (DOIs) for datasets and development of new tools and techniques for tracking data metrics will illustrate the scientific impact of CESD data.

A key goal of CESD's cyberinfrastructure development is to use innovative computational techniques to better enable the coupling of simulation, observational, and experimental data to support process science, evaluation of model simulations, and improvements

in predictability (see Fig. 12. Jet Stream Visualization, this page). Such techniques include more robust methodologies to quantify uncertainty; more sophisticated approaches involving adaptive grids, instrument simulators, data assimilation, and efficient input/output (I/O) methods; and improved methods for use of data for model initialization. CESD will continue to develop and support innovative testbeds, diagnostics, and metrics for evaluating models with observational and experimental data. CESD also will explore the use of models to improve collection of observational data through techniques such as Observation System Simulation Experiments (OSSEs) and analysis of model uncertainty to identify specific regions or processes for which more data are needed.

The cyberinfrastructure framework will improve consistency and compatibility across the hierarchy of models used by CESD scientists through integration of modern software practices including increased modularity and use of common code libraries, while moving toward a vision of interoperability across a range of models. Consistency across models of different scales and complexity will enable scientists to more easily inform simpler models with more complex ones, add higher resolution or more detailed process understanding for simulations of particular regions or phenomena, and couple models across disciplines as needed to address critical science questions.
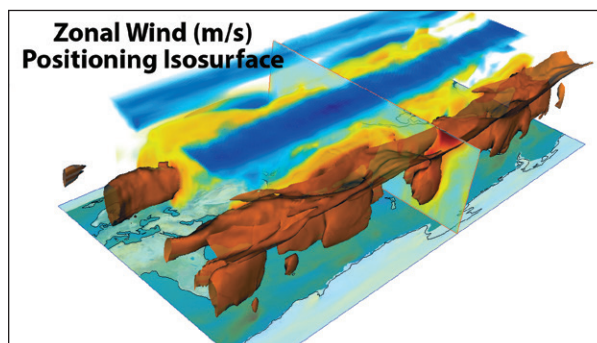
Fig. 12. Jet Stream Visualization. An interactive visualization of the jet stream (zonal wind velocity) using combined isosurface, slice, and volume renderers in vcs3D, the visualization component of Community Data Analysis Tools (CDAT) supported by DOE and the National Aeronautics and Space Administration (NASA). [Courtesy Thomas Maxwell, NASA Center for Climate Simulation, Goddard Space Flight Center]

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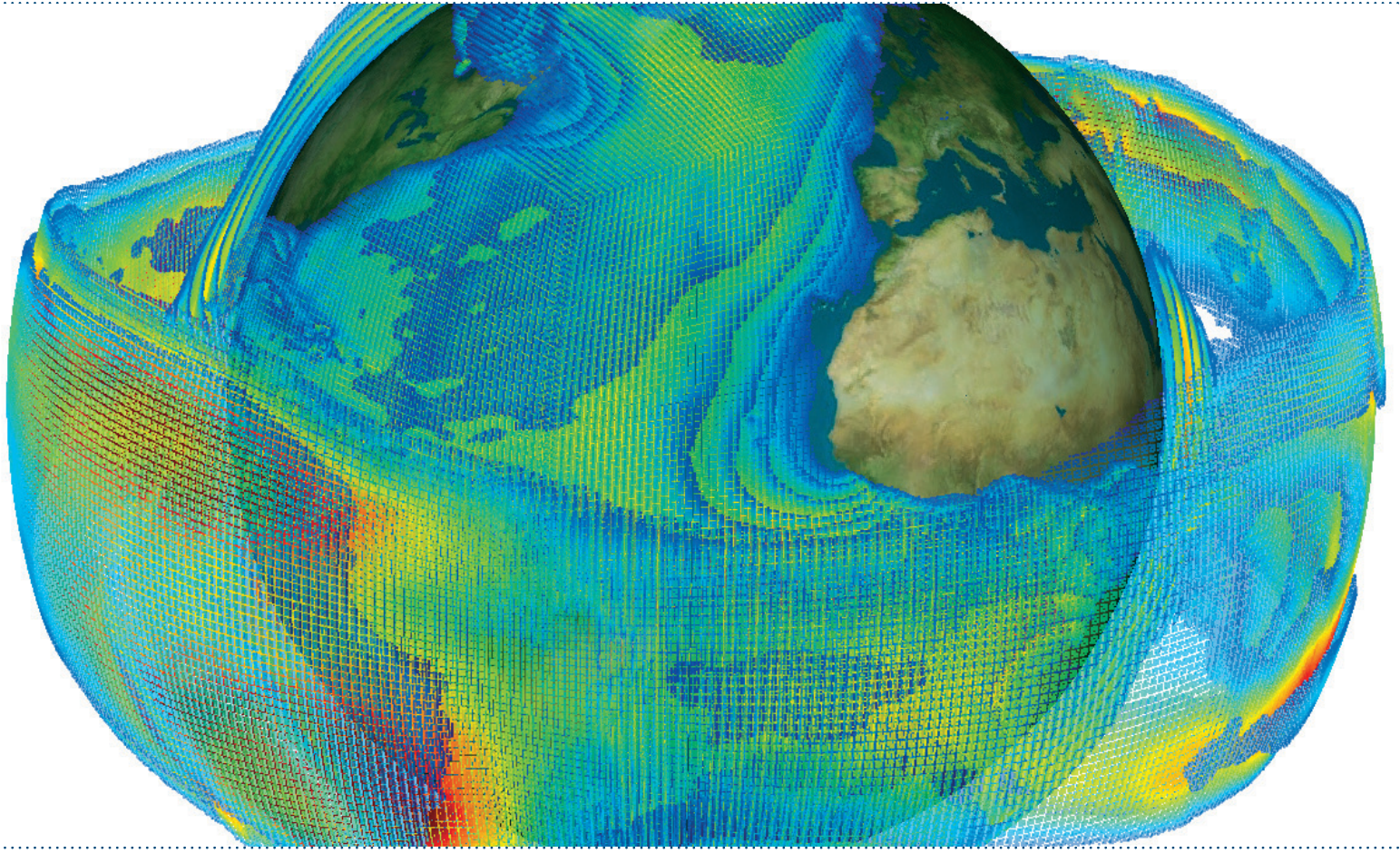
Implementation Strategy

Chapter 5
Implementation Strategy

The vision of the Climate and Environmental Sciences Division (CESD) is an improved capability for Earth system prediction across seasonal to multidecadal time scales to inform the development of resilient U.S. energy strategies. Complementing this vision, the CESD mission is to enhance this multiscale temporal predictability of the Earth system using long-term field experiments, Department of Energy (DOE) user facilities, modeling and simulation, uncertainty characterization, best-in-class computing, process research, and data analytics and management to inform the development of advanced solutions to U.S. energy challenges. The CESD vision and mission, while being science centric, are designed to inform applied science needs that address the mission and national security challenges across DOE.

As part of this strategy, core research projects supported by CESD and carried out by national laboratories and universities will, therefore, become increasingly complex, interdisciplinary, and collaborative to more rapidly advance the relevant science. The integrated model-observation-experiment paradigm (ModEx; see Fig. 2, p. 9) that was established in CESD's previous strategic plan is strengthened in this new plan. The 2018 plan's scientific focus emphasizes the need to understand system nonlinearities such as thresholds and tipping points, as well as potential system interdependencies. Because of this emphasis, CESD will prioritize investments that can lead to improved scale-aware, process-level understanding over time horizons that extend from the smallest-scale biogeochemical interactions to interdecadal oscillations acting on oceans, the atmosphere, and continents on the largest scale.

The five scientific grand challenges framing this strategy are sufficiently difficult to demand decadal-scale research efforts to make significant advancement and discovery. Even though this plan covers 5 years, CESD anticipates updating it periodically, based on scientific discoveries, new technical capabilities, and collaborative opportunities that are currently unknown. Therefore, CESD expects the plan to be dynamic, revisiting it every few years to evaluate progress and timeliness, as well as presenting opportunities for re-direction.

Furthermore, the ambition level for the grand challenges is sufficiently bold that no single program or agency can comprehensively address the plan's tough scientific questions without significant coordination and collaboration involving multiple agencies. For example, CESD's ambitions to advance the science of predictability on topics involving ocean dynamics, sea ice, ice, and ice sheets will require data gathered by other agencies such as the National Aeronautics and Space Administration (NASA), National Oceanic and Atmospheric Administration (NOAA), U.S. Geological Survey (USGS), and National Science Foundation (NSF). Joint funding of solicitations with these agencies is a potential avenue by which to leverage expertise and capabilities, and it also allows a more robust framework to reduce redundancy and maximize scientific output in support of multiple agency goals. In particular, emerging efforts across multiple agencies to advance understanding of the water cycle, including groundwater and the terrestrial-aquatic interface, will require coordination across modeling, data, and data assimilation disciplines at agencies including USGS, NOAA, U.S. Department of Agriculture, Department of Homeland Security, NSF, and Army Corps of Engineers. Without these interagency collaborations, DOE would not be able to easily achieve the new scientific advancements and capabilities that the nation so desperately needs. Other agencies will similarly achieve their goals more efficiently and cost-effectively through these collaborations.
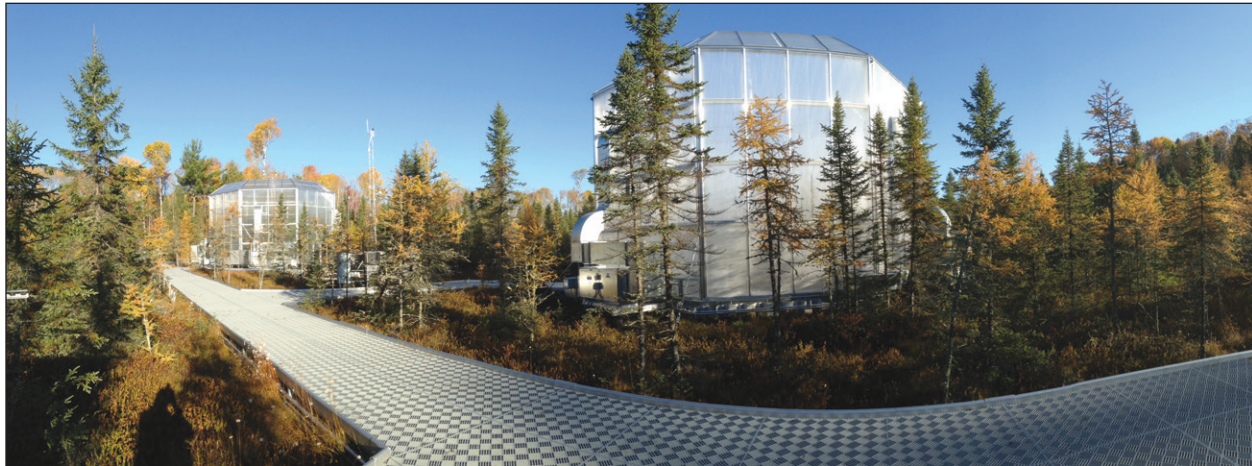
Fig. 13. Spruce and Peatland Responses Under Changing Environments (SPRUCE) Project. Experimental enclosures provide warming from the tree tops to the deep soil for the Terrestrial Ecosystem Science-supported SPRUCE project. SPRUCE is an ecosystem-scale manipulation study to assess the response of northern peatland ecosystems to increases in temperature and exposures to elevated atmospheric carbon dioxide concentrations. [Courtesy Oak Ridge National Laboratory]

The paradigm governing CESD's approach to implementation of this 2018–2023 strategic plan will continue to embrace the coupled ModEx template that was implemented during the past 5 years. With ModEx, field experiments will be organized based partly on deficiencies in model systems, and new knowledge gained from observational science will be rapidly incorporated into improved predictive capabilities. The Division anticipates that its continued commitment to the ModEx paradigm, together with increased attention to data and cyberinfrastructure developments, will enable CESD to shorten the time between discovery and societal benefit, thus increasing the value of science to stakeholders.

This strategic plan's implementation requires careful investments at DOE national laboratories as well as academic institutions. CESD views the national laboratories as intellectual hubs and integrators of DOE scientific investments. CESD's investments in the laboratories will continue to be dominated by long-term funding via the Science Focus Areas (SFAs) and long-term field experiments (see Fig. 13. Spruce and Peatland Responses Under Changing Environments Project, this page). As in the past, SFAs will continue to serve

as academic hubs for the community and emphasize an integrated, team-based approach to advance challenging multidisciplinary research that, in turn, exploits assets, capabilities, and facilities (e.g., Atmospheric Radiation Measurement User Facility, Environmental Molecular Sciences Laboratory, data, and computing) at participating DOE national laboratories. SFAs and their scientific teams also will be expected to demonstrate that they continually tap into the best ideas across the scientific community. To complement these core laboratory activities, CESD will continue to support smaller, yet focused research efforts at universities and other institutions. Other academic research will continue to be supported through targeted Funding Opportunity Announcements (FOAs) and Cooperative Agreements (CAs) that seek high-reward projects, which also may have high risk, that often align with or complement the longer-term national laboratory investments. CESD will increasingly align priorities within both laboratory and university communities to foster long-term growth for CESD science, thus meeting DOE's mission and national security challenges.

Addressing the scientific grand challenges described in Chapter 4 (see p. 12) requires careful coordination of

research portfolios and partnerships. Coordination of this multidisciplinary and multi-institutional approach to science is a difficult but recognized strength of DOE and CESD. CESD's scientific business model strives to build long-term, integrated research activities that benefit from the capabilities at the national laboratories in managing innovative, team-based projects and supplement that expertise with focused activities and expertise from the academic research community. The laboratories increasingly will be expected to propose and lead dedicated long-term projects, whereas the academics-based efforts will provide short-term targeted exploration of scientific issues, often addressing research questions that complement national laboratory research. Examples of successful multi-institutional scientific coordination that started in recent years include the Next-Generation Ecosystem Experiments (NGEE) in the Arctic and tropics, Energy Exascale Earth System Model (E3SM) project, and Subsurface Biogeochemical Research SFAs. These examples have resulted in multifaceted research that can exploit ideas and talent across the scientific community, meeting CESD's long-term vision and research objectives. Additionally, CESD will continue to embrace the need for open-source, community cyberinfrastructure frameworks that, in turn, support a broad range of programs and projects. Ultimately, this approach is expected to increasingly accelerate innovation and efficiency, as well as produce new science that will more rapidly advance system predictive capabilities.

To promote CESD's ambition to achieve challenging science, the Division will continue to regularly solicit and entrain the best ideas from the community via workshops, town halls, and conferences. These community outreach efforts are critical for identifying key research priorities within CESD's scientific grand challenges. On the federal level, CESD also will maintain a significant DOE presence within the relevant National Science and Technology Council subcommittees, such as the U.S. Global Change Research Program, to exchange information, coordinate strategies, and promote collaborative arrangements.

While the Division's managing organization, the DOE Office of Science, does not directly invest in education, CESD will continue to strongly endorse the entrainment of students and postdoctoral researchers as part of its university- and laboratory-funded projects and facilities. In addition, CESD will continue to participate in the DOE Office of Science Early Career and Graduate Student Research programs on topics in which the Division anticipates growth during the upcoming years. CESD also will maintain a strong commitment to diversity to achieve the goals outlined throughout this strategic plan.

CESD is excited about its new strategic plan. With a set of bold scientific research challenges and an approach to more rapidly assimilate new scientific research into more sophisticated predictive capabilities, the Division not only is committed to advancing basic science, but also is dedicated to building and enhancing the scientific careers of theoreticians, experimentalists, and modelers participating in the CESD community.

Appendices

Appendix 1
CESD Activity and Facility Descriptions

The Climate and Environmental Sciences Division (CESD) of the Office of Biological and Environmental Research (BER), within the U.S. Department of Energy (DOE) Office of Science, is organized around three disciplinary areas: atmospheric sciences, environmental sciences, and modeling. User facilities are included as part of the disciplinary studies. In addition to these areas, the Data Management activity supports the full breadth of CESD's research investments.

Atmospheric Sciences

Atmospheric Sciences research supported by CESD comprises the Atmospheric System Research (ASR) activity and its companion Atmospheric Radiation Measurement (ARM) User Facility. The goal of the ASR activity is to improve understanding of key cloud, aerosol, precipitation, and radiation processes that affect the Earth's radiative balance and hydrological cycle, especially processes that limit the predictive ability of regional and global models (see Fig. 14. Marine Cloud Drizzle, this page). For the most part, ASR investments use ARM's measurements of radiation, aerosols, clouds, precipitation, thermodynamics, turbulence, and state variables. ARM's continuous observational datasets are supplemented with process models, laboratory studies, and shorter-duration ground-based and airborne field campaigns to target specific atmospheric processes in different locations and across a range of spatial and temporal scales.

Atmospheric System Research

ASR has four priority research areas that correspond to atmospheric regimes with large uncertainties in Earth system prediction: aerosol processes, warm boundary layer processes, convective processes, and high-latitude processes. To better connect research teams working on the processes and process interactions within each

Fig. 14. Marine Cloud Drizzle. A drizzling marine stratocumulus cloud over the northeast Pacific Ocean. Marine low clouds represent one of the largest uncertainties and most important feedback factors in current-generation climate models. [Courtesy ARM User Facility]

of these areas, ASR is organized into four working groups that focus on objectives in their respective research areas.

Aerosol Processes Working Group: Seeks to improve the understanding of processes governing the spatial and temporal distribution of atmospheric particles and their chemical, microphysical, and optical properties.

Warm Boundary Layer Processes Working Group: Seeks to improve understanding and model representation of processes controlling the structural and radiative properties of clouds, aerosols, and their interactions with the underlying surface in the lowest few kilometers of the atmosphere.

Convective Processes Working Group: Seeks to improve the understanding and model representation of convective cloud processes and properties including

cloud cover, precipitation, life cycle, dynamics, and microphysics over a range of spatial scales.

High-Latitude Processes Working Group: Seeks to improve understanding and model representation of cloud, aerosol, and surface processes controlling the surface energy budgets in northern and southern high-latitude regions.

ASR-supported research results are incorporated into Earth system models (ESMs) supported by CESD both to understand the processes that govern atmospheric components and to improve ESM predictions of these processes.

Atmospheric Radiation Measurement User Facility

The ARM facility, a DOE Office of Science user facility, provides the scientific research community with strategically located *in situ* and remote-sensing observatories to improve the understanding and representation of relevant atmospheric processes in ESMs.

The ARM facility consists of three fixed observation sites; three mobile observatories; an aerial observation component; and infrastructure to collect, process, and deliver data to the research community. The three fixed sites are located in meteorologically distinct locations to sample continental and marine conditions in midlatitude and Arctic environments [i.e., U.S. Southern Great Plains (see Fig. 15. Radar Row, this page), the north slope of Alaska, and the Azores]. ARM also has three mobile facilities that can be used in variable-duration experiments across the Earth. ARM's aerial component complements the ground-based observations by providing information on spatial variability as well as detailed information on aerosol and cloud microphysical properties that can be obtained only through *in situ* measurements.

Each of ARM's fixed and mobile observatories contains a comprehensive set of cutting-edge, remote-sensing *in situ* instruments for measuring (1) the physical and radiative properties of aerosols, clouds, and precipitation; (2) the atmospheric state; and (3) detailed components of the surface

Fig. 15. Radar Row. In 2016, the ARM Southern Great Plains site reconfiguration took another step toward completion with the Raman lidar's reinstallation near the scanning radars, commonly referred to as ARM's radar row. [Courtesy ARM User Facility]

energy balance. Some observatories also contain co-located instrumentation for studying the impacts of land-atmosphere interactions on aerosols and clouds. ARM measurements are made at high temporal resolution and over extended time periods, providing statistically robust sampling of many different meteorological conditions. The ARM facility is continually updating its instrumentation and measurement strategies to provide the best data to the community.

ASR and ARM priorities for the next 5 years include:

1. Coupling ARM observations and high-resolution atmospheric models to accelerate the application of ARM observations for understanding key atmospheric processes.

2. Focusing on critical high-latitude aerosol and cloud processes through analysis and modeling projects leveraging targeted ARM measurements at the fixed site at Barrow, Alaska; the mobile observatory deployment at Oliktok Point,

Alaska; and two ship-borne mobile observatory deployments in the Southern Ocean and central Arctic Ocean.

3. Enhancing ARM's aerial capabilities including upgrades for an unmanned aerial system and tethered balloon systems, as well as replacement of the current G-1 aircraft, to enable critical *in situ* observations of the spatially variable structure of the atmosphere, aerosols, and clouds.

4. Developing data products, analysis tools, and computational capabilities that facilitate the scientific community's use of cutting-edge ARM instruments, such as scanning cloud radars.

5. Integrated studies of the key aerosol, boundary-layer, and convective processes driving aerosol-cloud-precipitation-surface-radiation interactions in continental, marine, and high-latitude environments.

Environmental System Science

The goal of Environmental System Science (ESS) is to advance a robust, predictive understanding of the set of interdependent physical, biogeochemical, ecological, hydrological, and geomorphological processes for use in ESMs and local-scale models.

ESS uses a systems approach to understand surface and subsurface ecosystems over multiple scales that can be represented in models [e.g., single-process models, system models, and DOE's Energy Exascale Earth System Model (E3SM)]. This emphasis on the capture of advanced understanding in models has two goals. First, it seeks to improve the representation of these ecosystem processes in coupled models, thereby increasing the sophistication of the projections from those models. Next, it exercises those models and compares the results against observations or other datasets to identify critical uncertainties that can inform future research directions.

The ESS research portfolio focuses on terrestrial ecosystems and processes that are regionally and globally important, climatically or environmentally sensitive, comparatively understudied or underrepresented in

ESMs and process models, and relevant to DOE's mission needs.

An important ESS focus area seeks to understand how watersheds function as complex hydrobiogeochemical systems and how these systems respond to perturbations (see Fig. 16. Flow Simulation Models, p. 29). Predictive understanding of the interactions between biogeochemical processes and hydrology will enable the quantification of watershed responses to a range of natural and anthropogenic perturbations. Thereby, this knowledge will enhance water and energy security by reducing the uncertainty in assessing the cost, waste, and environmental impacts of energy production, use, and disposition. This integrated hydrobiogeochemical perspective is particularly important for assessing the full extent of challenges posed by DOE's persistent contaminant plume issues and for developing approaches to manage them.

ESS has several current research emphases:

1. Understanding the role of disturbances in altering ecosystem functions or influencing Earth or environmental system forcing.

2. Gaining a mechanistic understanding of the role of belowground processes (e.g., microbiology, hydrobiogeochemistry, root or rhizosphere, and soil processes) in the terrestrial carbon and relevant biogeochemical cycles and their coupled feedbacks to the Earth and environmental systems.

3. Supporting large-scale coupled modeling and process research projects as well as large-scale, long-term ecosystem manipulations to understand environmental variability and response to change.

4. Expanding emphasis on the Arctic and boreal ecosystems and the role of their critical biogeochemical stocks and fluxes in a changing environment.

5. Addressing key relevant ecological and biogeochemical gaps in the understanding of terrestrial-aquatic interfaces at local to global scales.

6. Analyzing long-term ecosystem observational records to inform and evaluate models.

Fig. 16. Flow Simulation Models. Scientists seek to determine how perturbations (e.g., floods, drought, and early snow-melt) to mountainous watersheds affect the downstream delivery of water, nutrients, carbon, and metals over seasonal to decadal time scales through the development and testing of scale-adaptive models. [Courtesy Lawrence Berkeley National Laboratory]

7. Quantifying and predicting the mechanisms by which hydrology drives fine-scale biogeochemical processes and the exchange of water in coupled surface-subsurface systems.

8. Quantifying how biological behavior and feedbacks and abiotic-biotic interactions leading to molecular transformations influence mobility, transformation, fluxes, cycling, and fate of key nutrients, carbon, inorganic elements, and legacy DOE contaminants.

9. Translating information across relevant molecular to watershed scales.

10. Identifying, quantifying, and predicting watershed responses to natural and anthropogenic perturbations and shifts to new states.

11. Translating predictive understanding of watershed function and evolution to underpin environmental and energy strategies.

12. Encouraging exploratory research addressing previously unrecognized or innovative topics.

ESS seeks to connect its projects closely to other research activities within CESD, across BER, and in coordination or collaboration with other federal agencies. ESS activities will increase coordination with CESD's modeling activities by coordinating research solicitations and jointly funding projects. Examples of such coordination include Next-Generation Ecosystem Experiments (NGEE), E3SM co-development, International Land Model Benchmark project (ILAMB), Interoperable Design of Extreme-scale Application
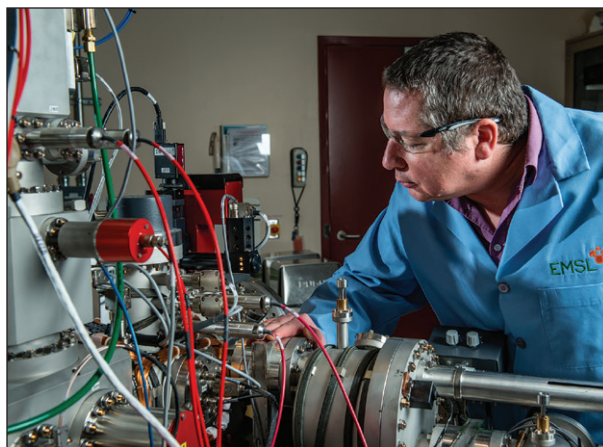
Fig. 17. NanoSIMS Instrument. Supporting studies in atmospheric science, biology, geochemistry, materials science, and nanoparticulates, EMSL's nanoSIMS instrument is a new-generation ion microprobe that extends secondary ion mass spectrometry (SIMS) analysis to extremely small areas or volumes while maintaining extremely high sensitivity at high mass resolution. [Courtesy EMSL]

Software (IDEAS) project, hydrology modeling frameworks, and land-atmosphere measurements. In addition, ESS management will, in adhering to the 2018 strategic plan, forge stronger programmatic coordination with other CESD user research areas [e.g., Data Management and the Environmental Molecular Sciences Laboratory (EMSL) user facility]; ESS also will increase coordination with the Genomic Science Program (within BER's Biological Systems Science Division).

ESS will reinforce its historical coordination with DOE priorities involving environmental management and expand its engagement with other agencies involved in the modeling of hydrological and ecological systems (e.g., National Oceanic and Atmospheric Administration and U.S. Geological Survey).

Environmental Molecular Sciences Laboratory

EMSL is a DOE Office of Science user facility located at Pacific Northwest National Laboratory in Richland, Washington. EMSL advances discovery and mechanistic understanding at the molecular to mesoscale of biological, chemical, and physical processes and interactions that underpin systems-level biological,

environmental, and energy challenges. EMSL provides scientists with access to a wide range of premier instruments for experimental research, as well as the capacity computing and data analytics that enable users to validate simulations and conduct model-driven experimentation across a range of temporal and spatial scales (see Fig. 17. NanoSIMS Instrument, this page).

EMSL is strategically aligned with the DOE mission to ensure the security and prosperity of the United States by enabling transformative science and technology development. EMSL also supports the Office of Science and BER priorities to understand natural and anthropogenic inputs to Earth and its environmental system processes, improve predictions of key environmental and atmospheric processes, and obtain a systems-level understanding of how genomic information is translated into functional capabilities of living systems. User science at EMSL is driven by science themes that reflect Office of Science and BER strategic directions and EMSL's scientific expertise.

EMSL provides the community with access to scientists and capabilities for microscopy, tomography, spectroscopy, spectrometry, sensing, cell culture, sequencing, elemental detection and deposition, and other analyses. It also makes available capacity computing and associated software codes for modeling atomic and molecular chemistry, molecular and structural dynamics, metabolic processes, reactive transport, and continuum processes. EMSL maintains premier experimental capabilities and advances scientific techniques through procurements and internal design-and-build projects that result in new instruments and significantly enhance existing capabilities. EMSL scientists create, make use of, and enhance open-source computational codes to meet their evolving computational needs.

EMSL collaborations enable users to obtain insights into the fundamental mechanisms that influence biological and environmental system science. These areas include elemental and nutrient cycling and transport in soils, groundwater, watersheds, and terrestrial environments; land-atmosphere interactions and aerosol particle formation, evolution, and atmospheric transport; rhizospheric processes; microbial, mineral, and contaminant interactions; intracellular interactions

and metabolism in bacteria, archaea, fungi, and plants; microbial, fungal, and plant community interactions; and biodesign for bioenergy.

EMSL priorities for the next 5 years include:

1. Understanding the cycling, transformation, and transport of critical biogeochemical elements (e.g., carbon, nitrogen, sulfur, potassium, manganese, iron, and calcium), water, contaminants, particulates, and other complexes and materials.

2. Understanding biological processes, interactions, and signaling within microbial (i.e., archaea, bacteria, and algae), fungal, and plant cells; among cells in communities; and between cellular membrane surfaces and their local hydrobiogeochemical environment.

3. Investigating how microbial, geochemical, and physical interactions enable "hot spots" and "hot moments" of biological activity that influence Earth system processes and dynamics and contaminant transformations and transport.

4. Characterizing the Earth system's fundamental biogeochemical, hydrological, microbial, vegetative, and ecological processes and their interfaces and interactions, from molecular to mesoscale.

5. Incorporating the physical, chemical, and biological structural components of the living Earth system and their mechanistic interactions, kinetics, and other functional information into appropriate mechanistic and multiscale models.

Earth and Environmental Systems Modeling

The goal of Earth and Environmental Systems Modeling (EESM) is to simulate and understand DOE-relevant predictability of the Earth system by describing processes and process interactions over multiple temporal and spatial scales. EESM investments focus on model development, model analysis, and understanding of the role of multisector interactions with the physical-human system. The vision for EESM is to provide DOE with the best possible information about the evolving Earth system, so that, for example, energy assets and infrastructures remain robust throughout their lifetimes. Key examples of critical Earth system information supporting the DOE mission include projections of water availability, drought incidence and persistence, temperature extremes such as prolonged heat stress, probability of storms, opening of the Arctic Ocean, and convolved sea-level and storm-surge interactions with coastal regions. To provide this information, considerable effort is needed to develop optimum-fidelity Earth system simulations, with suitably accurate representations of atmospheric dynamics, clouds and chemistry, ocean circulation and biogeochemistry, land biogeochemistry and hydrology, sea ice and dynamic land ice, and in each case including elements of human activities that affect these systems such as water management and land use.

EESM uses the mathematical and computational expertise within DOE laboratories, often in partnership with academia. Together, laboratory and university researchers coordinate and collaborate to produce more creative insights and innovations to explain complex phenomena. These researchers employ, for example, efficient, accurate, and advanced algorithms for Earth system processes; improved methods for model initialization; optimal component coupling and uncertainty of system simulation; and scale-aware climate projections. A major goal is to optimize Earth system codes to run efficiently on DOE's best-in-class high-performance supercomputers, using modern and sustainable software and workflows and providing accessibility to high-resolution, coupled Earth system simulation capability for energy and related sector requirements.

Central to the EESM activity is the Energy Exascale Earth System Model (E3SM) project, launched by BER in 2014 and released for open scientific research in April 2018. The E3SM project team is dedicated to the development of an efficient, high-resolution Earth system model that runs on DOE high-performance computers, simulating the near-term past (e.g., for model validation) and future (e.g., 3 to 4 decades) in support of DOE science and DOE's mission. The E3SM project designs and
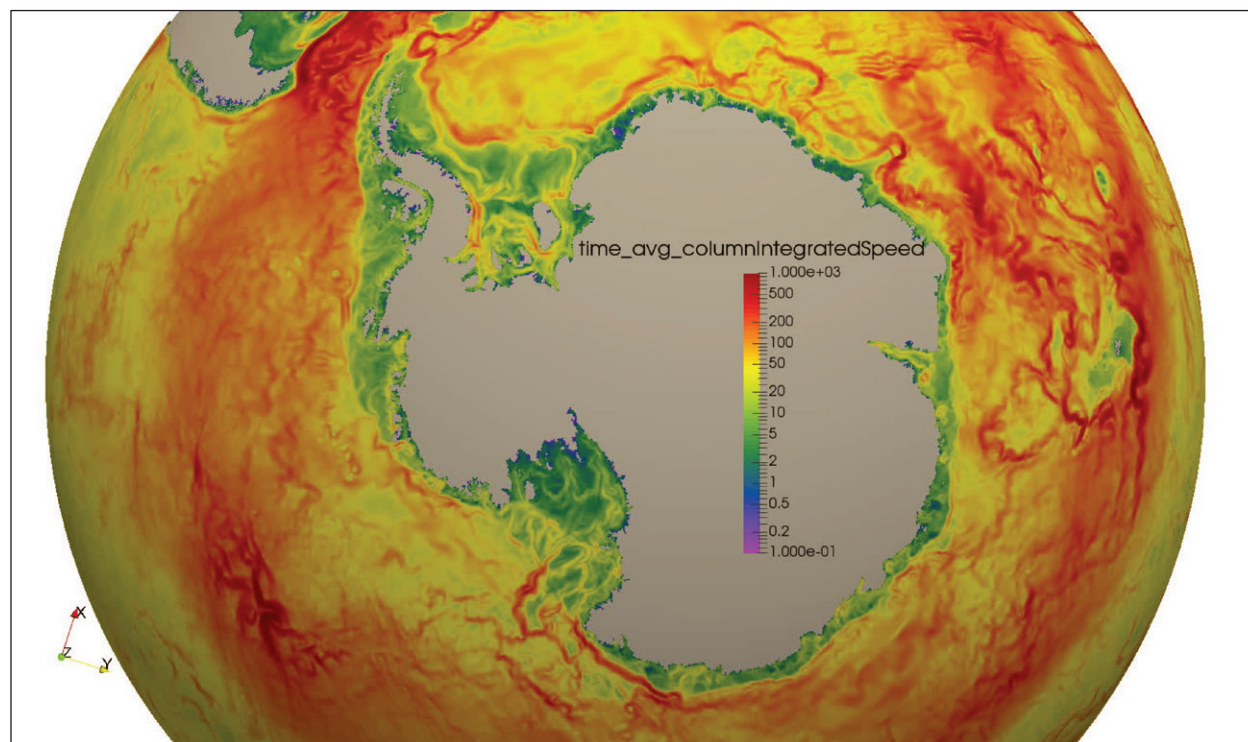
Fig. 18. Coupled Ocean–Sea Ice Simulation. Time-averaged, column-integrated ocean speed (m/s) from a global, high-resolution, coupled ocean–sea ice simulation that includes ocean circulation under Antarctic ice shelves. This unique E3SM capability is being used to better understand and explore the causes and effects of increased submarine melting of Antarctic ice shelves in the context of sea-level rise from ice sheets. [Courtesy Los Alamos National Laboratory]

performs high-resolution Earth system simulations, targeting the research community's more challenging science questions, such as those involving water cycle science, cloud-aerosol interactions, ice-sheet physics and dynamics, biogeochemical cycles, ocean-eddy dynamics, and the interdependence of low-frequency variability and extreme weather (see Fig. 18. Coupled Ocean–Sea Ice Simulation, this page). Other EESM-supported activities complement and enhance E3SM, including the development of future-generation E3SM capabilities within the Scientific Discovery through Advanced Computing (SciDAC) activity, which is a partnership with BER and DOE's Office of Advanced Scientific Computing Research (ASCR), and supporting collaborative and community codes that are developed and used by multiple climate and weather groups.

Given that no single modeling approach can adequately represent all observed behaviors of the Earth system, EESM also invests in the use of hierarchical models ranging from the most complex high-resolution climate models (e.g., E3SM) to superparametrized models using nonhydrostatic physics and land use–sector models that incorporate changing landscapes. EESM also uses idealized configurations of complex models and reduced-complexity models for hypothesis testing. Configuring, diagnosing, and evaluating the complex behavior of models through systematic comparison with available observations represent core capability investments that are critical to CESD's strategy.

Coordinated with and complementing the E3SM capability are research investments involving physical system interactions with energy, water, and other land-use

Fig. 19. Collaborative Modeling Research. Scientists supported by the Multisector Dynamics activity in the EESM research area are discovering the potential implications of Earth system changes on land use, bioenergy production, and agricultural yields. [Courtesy DOE Great Lakes Bioenergy Research Center]

sectors. More specifically, multisector analysis strives to advance scientific understanding of the complex interactions, interdependencies, and co-evolutionary pathways within the human-Earth system, including nonlinear system behaviors, the potential for cascading failures among sectors and infrastructures, and feedbacks within the coupled system. Particular emphasis is placed on understanding the energy-water-land nexus at regional and subregional scales that, in turn, incorporates elements of land-use change, socioeconomic evolution, and decision theory (see Fig. 19. Collaborative Modeling Research, this page). A particular focus includes model development and improvements, which can be used to understand how extreme events influence the physical, biogeochemical, and multisector components of the Earth system, as well as how the component interactions can influence future extremes.

Because variability and change within the Earth system are highly nonlinear and regionally dependent, the EESM activity has developed a multifaceted, multisystems approach to understanding how the system works

over various temporal and spatial scales. This approach involves research to probe and understand the physical, chemical, and biological drivers and feedbacks acting both within and between the atmospheric, oceanic, terrestrial, cryospheric, and human components. Analysis takes the form of simulation using multiple model types and the use of novel diagnostic and machine-learning techniques. The role of clouds, biogeochemistry, extreme statistics, and low-frequency variability are used to explore causes of variability and change, as well as the uncertainties, in regions of interest to both science and DOE.

EESM strategic goals for the coming decade include:

1. Ongoing development of the high-resolution, regionally refined E3SM with advanced software and workflows to run efficiently on continually advancing computational architectures.

2. Ongoing development of scale-aware atmospheric physics parameterizations based on ARM and other data for use in next-generation large eddy simulations and both regional and global Earth system models.

3. Continued development of energy, water, agriculture, and other sector models as part of regional and global Earth system models, including E3SM, to analyze co-evolution and sector interdependencies in response to extreme phenomena and recovery.

4. Development of advanced and efficient methods for characterizing how Earth system uncertainty affects uncertainty in the projected changes for the coupled system.

5. Optimization of observational requirements needed for global Earth system model calibration, bias-reduction, and effective high-resolution initialization.

6. Regionally refined versions of E3SM for areas of particular interest to CESD science and the DOE mission, including polar regions, coastal regions, and the United States.

Fig. 20. Environmental System Science-Data Infrastructure for a Virtual Ecosystem (ESS-DIVE). The ESS-DIVE long-term vision is to provide a data archive that enables ESS research through community engagement. Key: DOI, digital object identifier. [Courtesy Lawrence Berkeley National Laboratory]

7. Improved understanding of the dynamics governing precursors and evolution of extreme events and their relationships to teleconnections.

8. Improved representation of land systems that incorporate application-appropriate detail of hydrobiogeochemistry and microbial communities, particularly in regions exposed to rapid change and sharp spatial gradients (e.g., coastal regions).

9. Further analyses of variabilities and change based on robust techniques involving metrics, diagnostics, machine learning, and multiscale analysis.

Data Management

The Data Management (DM) activity within CESD emphasizes data standards, preservation, and federation to benefit all DOE scientists. To date, the DM

activity supports the Earth System Grid Federation (ESGF) and ESS Data Infrastructure for a Virtual Ecosystem (ESS-DIVE; see Fig. 20. ESS-DIVE, this page).

A general goal of this activity is to develop and make available to the community novel, scale-aware visualization and analysis methods involving observational and model-generated data. The DM activity also prioritizes the further development of tools to quantify uncertainty and adapt to different modeling frameworks that will enable integrated analysis and comparison of data from multiple sources and across variable experimental conditions. The massive volumes of data and the demand for data security require a federated data archiving and dissemination construct. Short-term goals are to develop user-focused publication tools, using an open-source scripting approach, that are required to organize, manipulate, and publish data; design visualization and analytics tools by leveraging existing community capabilities and interfaces that allow multiscale data analytics and model integration; and demonstrate capabilities within existing federated constructs.

While CESD supports many activities with integrated experimental and computational functions, dramatic improvements in technologies and analytic methodologies during recent years have shifted the bottleneck in scientific productivity from data production to new opportunities and challenges in data interpretation and visualization. For example, novel computational strategies for integration and interpretation of information generated from different scales are needed to further explain the underlying design principles of different system elements and the association between different phenomena. Statistical data analytics, machine learning, and inference are central to virtually all scales of data analytics in the climate, Earth, and environmental sciences, and this activity will pursue all of them.

Given that data volumes already exceed exabyte scales, the federated data system approach adopted by CESD will need future expansion. This advancement will require that data providers maintain a set of

geographically dispersed nodes accessible by the scientific community and that, through linkages, these nodes increasingly will be required to serve as archived data repositories. Thus scientists will be able to access all data as if that data were on their own system (see Fig. 21. ESGF's Decentralized Approach, this page). Such an integrative system also will require pro-totyping of new algorithms for new model representations, uncertainty quantifica-tion, and intelligent pattern recognition (BERAC 2013).
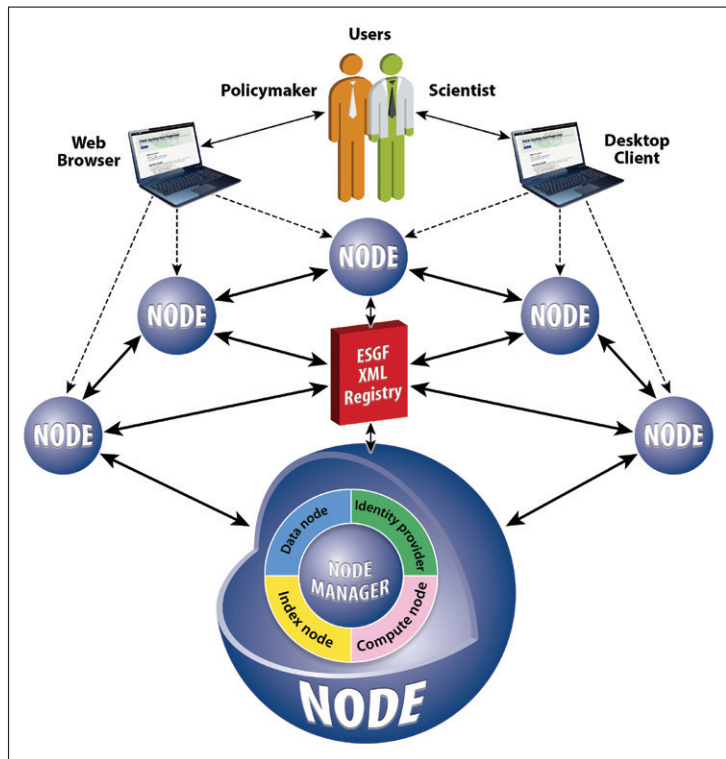

Fig. 21. Earth System Grid Federation's (ESGF) Decentralized Approach. ESGF ensures equal access to large disparate datasets (e.g., simulation, observation, and reanalysis) that in the past would have been accessible across the climate science community only with great difficulty. The ESGF infrastructure enables scientists to evaluate models, understand their differences, and explore the impacts of climate change through a common interface, regardless of data location.

Appendix 2
References

BERAC. 2013. *BER Virtual Laboratory: Innovative Framework for Biological and Environmental Grand Challenges; A Report from the Biological and Environmental Research Advisory Committee*, DOE/SC-0156 (science.energy.gov/~/media/ber/berac/pdf/Reports/BER_VirtualLaboratory_finalwebHR.pdf).

BERAC. 2017. *Grand Challenges for Biological and Environmental Research: Progress and Future Vision; A Report from the Biological and Environmental Research Advisory Committee*, DOE/SC–0190, BERAC Subcommittee on Grand Research Challenges for Biological and Environmental Research (science.energy.gov/~/media/ber/berac/pdf/Reports/BERAC-2017-Grand-Challenges-Report.pdf).

U.S. DOE. 2012. *Climate and Environmental Sciences Division Strategic Plan*, DOE/SC-0151, U.S. Department of Energy Office of Science (science.energy.gov/~/media/ber/pdf/CESD-Strat-Plan-2012.pdf).

U.S. DOE. 2014. *U.S. Department of Energy Strategic Plan, 2014–2018*. U.S. Department of Energy (www.energy.gov/sites/prod/files/2014/04/f14/2014_dept_energy_strategic_plan.pdf).

Appendix 3
Chapter Cover Image Descriptions and Credits

 Chapter 1: Mission. Treeline along an elevational gradient in the Colorado Rockies, where Terrestrial Ecosystem Science-supported researchers are studying the effects of climate warming on mountain-top plants and soils. [Courtesy Aimee Classen, University of Vermont]
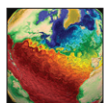
 Chapter 2: Vision and Values. Visualization of global water-surface temperatures, with the surface texture driven by vorticity. Cool temperatures are designated by blues and warmer temperatures by reds. Trapped regions of warmer water (red) adjacent to the Gulf Stream off the U.S. East Coast indicate the Model for Prediction Across Scales-Ocean's (MPAS-O) capability to simulate eddy transport of heat within the ocean, a key component necessary to accurately simulate global climate change. [Courtesy Los Alamos National Laboratory]
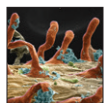
 Chapter 3: Plan Background and Purpose. Magnified view of a red pine (*Pinus resinosa*) root and associated microbiome. [Courtesy Environmental Molecular Sciences Laboratory]

 Chapter 4: CESD Scientific Grand Challenges for 2018–2023. Images represent a broad range of natural systems that drive CESD-supported science. These systems are not only structurally and spatially complex with many different interacting parts spanning molecular to global scales, but they are also spatially complex, encompassing processes that occur over time scales ranging from nanoseconds to centuries. [Ball-and-stick representation of atoms within a molecule, Pacific Northwest National Laboratory. Ribosome molecular complex image, Ditlev Brodersen, Aarhus University. Magnified view of a red pine (*Pinus resinosa*) root and associated microbiome, Environmental Molecular Sciences Laboratory. Forest ecosystem image, U.S. National Park Service. Mountain and Earth images, iStockphoto.com.]
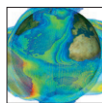
 Chapter 5: Implementation Strategy. Interactive volume rendering of cubed sphere data using vcs3D, the visualization component of Community Data Analysis Tools (CDAT) supported by the Department of Energy and the National Aeronautics and Space Administration (NASA). [Courtesy Thomas Maxwell, NASA Center for Climate Simulation, Goddard Space Flight Center]

 Appendices. Installation of an aquifer tube to monitor the hydrological exchange of river water and groundwater and associated biogeochemical processes in the Hanford Reach of the Columbia River. This work is supported by the Subsurface Biogeochemical Research activity. [Courtesy Pacific Northwest National Laboratory]

Acronyms and Abbreviations

ARM   Atmospheric Radiation Measurement

ASCR   DOE Office of Advanced Scientific Computing Research

ASR   Atmospheric System Research

BER   DOE Office of Biological and Environmental Research

BERAC   Biological and Environmental Research Advisory Committee

CESD   BER Climate and Environmental Sciences Division

DM   Data Management

DOE   U.S. Department of Energy

E3SM   Energy Exascale Earth System Model

EESM   Earth and Environmental Systems Modeling

EMSL   Environmental Molecular Sciences Laboratory

ESGF   Earth System Grid Federation

ESM   Earth system model

ESS   Environmental System Science

ESS-DIVE Environmental System Science-Data Infrastructure for a Virtual Ecosystem

ModEx   integrated model-observation-experiment paradigm

NASA   National Aeronautics and Space Administration

NGEE   Next-Generation Ecosystem Experiments

NOAA   National Oceanographic and Atmospheric Administration

NSF   National Science Foundation

SFA   Science Focus Area

USGS   U.S. Geological Survey