WRITTEN TESTIMONY OF

Dr. Xubin Zeng
Agnese N. Haury Chair and Professor,
Department of Hydrology and Atmospheric Sciences,
University of Arizona, Tucson, Arizona

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Introduction

Chairman Bowman, Ranking Member Weber, and members of the Subcommittee, thank you for the opportunity to be here today to discuss climate and environmental science research in the Biological and Environmental Research (BER), Office of Science, Department of Energy (DOE).

My name is Xubin Zeng and I am the Agnese N. Haury Chair in Environment, Professor of Atmospheric Sciences, and Director of the Climate Dynamics and Hydrometeorology Center at the University of Arizona. I am also an affiliated professor of the Applied Mathematics, Global Change, and Remote Sensing and Spatial Analysis Interdisciplinary Programs. I am an elected fellow of both the American Meteorological Society (AMS) and American Association for the Advancement of Science. I served on the Governing Board of AMS and its Executive Committee, and received the AMS Charles Franklin Brooks Award for Outstanding Service to the Society in January 2021. I also received the Special Creativity Award from the National Science Foundation (NSF), the Outstanding Faculty Award from the University of Arizona's Asian American Faculty, Staff and Alumni Association, and the Colorado State University Atmospheric Science Outstanding Alumni Award.

Relevant to the topic of today's hearing, starting this week, I begin to co-chair the Scientific Steering Group of the Global Energy and Water Exchange (GEWEX) Project – one of the major international programs on climate and water science. I also serve on the Science Advisory Board of the Earth & Biological Sciences Directorate of DOE Pacific Northwest National Laboratory, and the Science Advisory Board Environmental Information Services Working Group of the National Oceanic and Atmospheric Administration (NOAA). In the past decade, I co-chaired the National Aeronautics and Space Administration (NASA) Earth Science Community Workshop and White Paper on future directions in the Weather Focus Area, chaired the Community Workshop and White Paper on lower-atmosphere observing facilities for climate studies for the NSF Division of Atmospheric and Geospace Sciences, chaired the NOAA white paper on the use of observing system simulation experiments which was forwarded to the U.S. Congress, and served on the National Academies Board on Atmospheric Sciences and Climate and the NASA/NOAA/USGS Earth Science Decadal Survey Weather and Air Quality Panel.

My testimony today draws on my above experiences and my publication record of over 200 peer-reviewed papers on land-atmosphere-ocean interface processes, weather and climate modeling, hydrometeorology, remote sensing, nonlinear dynamics, and big data analytics. In particular, it draws on my research and my extensive interactions with DOE and other scientists on the science and user facilities related to the topic of today's hearing.

This testimony is organized into four brief sections: 1) current status of DOE's climate and environmental systems research, 2) unique aspects of these research efforts, 3) major challenges, and 4) future directions.

1) What is the current status of DOE's climate and environmental systems research?

DOE Office of Science manages its research portfolio through six program offices, including Biological and Environmental Research (BER). BER has two divisions, including the Earth and Environmental Systems Sciences (EESS) Division. The EESS Division supports fundamental science and research capabilities that enable major scientific developments in Earth system-relevant atmospheric and ecosystem process and modeling research in support of DOE's mission goals for transformative science for energy and national security. All of DOE's climate science research is housed within the EESS Division which supports three primary research activities:

- Atmospheric System Research Program addresses a main source of uncertainty in Earth system models: the interdependence of clouds, atmospheric aerosols, and precipitation that in turn influences the Earth's radiation balance. This Program works closely with the Atmospheric Radiation Measurement (ARM) user facility in support of its activities.
- Environmental System Science Program supports research to provide an integrated, robust and scale-aware predictive understanding of environmental systems, including the role of hydro-biogeochemistry from the subsurface to the top of the vegetative canopy. Experimental and modeling research is supported in part by capabilities at the Environmental Molecular Sciences Laboratory (EMSL).
- Earth and Environmental Systems Modeling Program supports three areas:
    - to develop physical, chemical, and biological model components, as well as fully coupled Earth System Models;
    - to develop multi-sector (e.g., energy, water, agriculture) dynamics models for human system and integrated human-Earth system modeling; and
    - to enhance a predictive understanding of variability and change within the Earth System through modeling and data analysis.

  In particular, the first program area supports the Energy Exascale Earth System Model (E3SM), which is a world-class, variable-resolution climate model that is run on DOE's Leadership Computing Facility supercomputers.

In addition, the EESS Division supports two scientific user facilities:

- ARM provides unique, multi-instrumented capabilities for continuous, long-term observations and mobile facilities as well as model–simulated high resolution information to improve understanding and test hypotheses involving the role of clouds and aerosols on the atmosphere's solar and terrestrial radiative balance over a variety of spatial scales; and

- EMSL provides world-class laboratory equipment and integrated experimental and computational resources to extend understanding of the physical, biogeochemical, chemical, and biological processes that underlie DOE's energy and environmental mission.

To illustrate the success of these activities, here I provide three examples. First, E3SM version 1 was released in 2018, including a unique capability of regional refinement in all of its components for high resolution modeling. E3SM results at both low (~100 km) and high (~25 km) resolutions are used in the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6). More recently, a new global cloud-permitting modeling capability at 3 km grid spacing has been developed and demonstrated through participation in an international effort to intercompare global cloud-permitting simulations, making E3SM the world's highest resolution climate prediction capability. These simulations show substantial improvements in addressing longstanding model biases (with a grid spacing of ~100 km) such as the diurnal cycle of precipitation – which is the focus of an international project led by a DOE E3SM scientist.

ARM developed and implemented the LES (Large-Eddy Simulation) ARM Symbiotic Simulation and Observation (LASSO) workflow. LASSO uses ARM observations to constrain and evaluate LES simulations to provide high-resolution (100 m grid spacing), three-dimensional datasets for studying atmospheric processes. Besides the LES simulations of shallow cumulus clouds over the Southern Great Plains ARM site, LASSO has recently been expanded to study deep convection and heavy precipitation in conjunction with a major ARM field campaign in Argentina and to study marine stratocumulus clouds, which is crucial for the Earth's radiation balance, at the Eastern North Atlantic atmospheric observatory established by ARM.

As part of the Earth and Environmental Systems Modeling Program, the multi-sector dynamics program area has been further developed in order to extend beyond the more constrained emphasis on Integrated Assessment Modeling. This (MultiSector Dynamics) program area has launched a Community-of-Practice to explore the co-evolution of human and natural systems over time and to build the tools that bridge across sectors (energy, water, land, economy) and scales (spatial, temporal). Furthermore, the Global Change Analysis Model (GCAM), which represents many of the interactions among human and Earth system, has been in continuous development by this program area and is currently being incorporated into E3SM. Given this, E3SM is the only climate model that includes details on the human component (i.e., infrastructures, economics, land use, etc.) that is built within the prediction modeling framework.

2) What is unique about these research efforts?

Research efforts supported by the BER EESS Division are part of the interagency U.S. Global Change Research Program (USGCRP), that in turn is comprised of 13 federal agencies that conduct or use research on global change and its impacts on society, in support of the Nation's response to global change. Here I identify four unique aspects of DOE's climate and environmental systems research.

First, there are ~50 Earth system models in the world. E3SM stands out for having a close integration with DOE's world-leading high-performance computing. Indeed, "exascale" computing is even included in the name of E3SM. While supercomputer speed can be measured and benchmarked, the actual speed realized in modeling strongly depends on the model architecture and software. By optimizing the E3SM code for DOE's advanced computers, DOE not only maximizes its ability to leverage its own resources but is also developing new knowledge and best practices that will improve other models worldwide. E3SM is the first model of its kind to be run on the ultra-fast supercomputers, i.e., exascale computers, developed by DOE.

Another unique aspect is DOE's heavy emphasis on extreme events (e.g., hurricanes) and geographic domains that exhibit sharp gradients (e.g., coastlines and complex terrain over western U.S.) in the context of larger-scale and longer-term changes such as the global warming and other climate changes induced by greenhouse gas increases and other human activities. This is done, for example, through E3SM's unique capability of regional refinement in all of its components for high resolution modeling. Recent progress in the development of a GPU (graphics processing unit)-enabled, rather than the traditional CPU (central processing unit)-based, version of the E3SM global cloud permitting model, will further enhance E3SM's ability to resolve extreme events and tight spatial gradients in the context of a global Earth system model that can simulate multi-decadal changes. Complementing the modeling of these complicated regions, DOE also supports long term field experiments such as in the Arctic, Tropics, and mid-latitude U.S. sites, to calibrate, validate, and test predictive models with a focus on characterizing and reducing prediction uncertainty.

GCAM is one of only a handful of integrated human-simplified Earth system models that has contributed scenarios (e.g., Representative Concentration Pathways and Shared Socioeconomic Pathways) to drive climate model simulations in all of the IPCC's major assessment reports, including AR5 and AR6, as well as other important community activities such as the Coupled Model Intercomparison Projects (CMIP5 and CMIP6). One weakness of current approaches used by most climate modeling centers is that the greenhouse gas concentrations at the end of 21st Century from these scenarios would be different from those using Earth system models with the same natural and anthropogenic emissions. To avoid this inconsistency, GCAM is being integrated into E3SM, which represents the world's first attempt to develop a fully coupled human-Earth system model to make more consistent and realistic predictions.

Both ARM and EMSL are world-leading user facilities in the relevant fields. For instance, ARM provides the world's most comprehensive, continuous, and precise observations of clouds, aerosols, and related meteorological information. This is done through a combination of ground-based measurements and aerial measurements with piloted aircraft, unmanned aerial systems and tethered balloon systems. This comprehensive "supersite" observatory approach is now widely adopted by other national and international programs. Besides supporting BER atmospheric sciences and Earth system modeling research, the ARM facility freely provides key information to other agencies; e.g., for calibration and validation of space-borne sensors at NASA.

3) What are the challenges for DOE's climate and environmental systems research?

To continue DOE's leadership in climate and environmental systems research, several major challenges will need to be addressed.

First, to further enhance the integration of Earth system modeling with exascale computing, there are a number of scientific and software engineering challenges. For instance, while the numerical solution of partial differential equations for atmospheric dynamics (e.g., for the movement of water vapor by wind in the atmosphere) has been traditionally emphasized, the numerical solution of physical, chemical, and biological processes (e.g., aerosols, clouds, precipitation, radiation, turbulence), interactions among these processes, and their interaction with atmospheric dynamics have not received enough attention. Additionally, there is an urgent need to develop approaches that take maximum advantage of both GPU- and CPU-based computing, which is a paradigm shift for many Earth system modelers, who have traditionally emphasized CPU-based architectures. These challenges can be addressed through the Scientific Discovery Through Advanced Computing (SciDAC) Program jointly supported by BER and DOE's Office of Advanced Scientific Computing Research and through DOE Office of Science's Graduate Student Research Program (to develop the future pipeline in this area).

Understanding Earth system predictability (which represents the upper bound of prediction using physics-based equations) is already recognized as a multi-agency grand challenge in the U.S. It is even more challenging to understand the predictability of the fully coupled human-earth system. New understanding is urgently needed through innovative theoretical studies, global data analysis, and global modeling of human, natural, and coupled human-natural systems. It is unclear if current global models are adequate for predicting extreme events, as such models may contain numerical and spurious chaos and may dampen extreme events. Also needed is the use of innovative Artificial Intelligence (AI)/Machine Learning (ML) approaches to address predictability issues in both human and natural systems, such as the prediction of extreme events as the climate evolves.

A major goal of BER's modeling efforts is to help examine the resilience of our Nation's infrastructure, especially energy infrastructure and its interaction with other sectors such as water systems and land use changes, and to help inform energy infrastructure investment decisions and national security. This requires smaller horizontal model grid spacing (e.g., using the global cloud-permitting model at 3 km grid spacing), better representation of important processes (e.g., cloud-aerosol, water cycle, biogeochemistry, and the cryosphere) assisted by ARM and EMSL user facilities, better understanding of how human activities influence and are influenced by climate change, and quantification and possible reduction of key uncertainties, based on integration of AI/ML with physics-based approaches. Also needed are the close interactions between BER activities and DOE's applied energy programs.

To continue the leadership of the ARM and EMSL user facilities, the challenge is to keep up with new observing technologies, develop new capabilities, and provide better user support to enhance the user base and scientific and societal impacts. For example, the newly acquired manned aircraft significantly enhances ARM's aerial capabilities. The ARM data center currently holds over 2 Petabytes of data from over 11,000 datasets and these numbers are steadily increasing. While ARM is doing an excellent job in access and stewardship, the challenge is on data discovery, visualization, and tailored needs of users.

4) What are the future directions of DOE's climate and environmental systems research?

Based on the above discussions, the future directions include:

Coupled model development. A GPU-enabled version of the E3SM global cloud-permitting model (with a grid spacing of 3 km) should continue to be developed for exascale computers. Scale-aware parameterizations of physical, chemical, and biological processes need to be developed for a unified model applicable and skillful at resolutions ranging from 3 – 100 km. In addition, GCAM at even higher resolution should be further integrated into E3SM. Currently, the primary interactions between the two codes are with respect to biogeochemistry and land surface changes, but more complete integrations (e.g., water demand from GCAM influencing water availability in E3SM) are needed.

To further accelerate coupled human-earth system modeling, AI/ML approaches should be explored:

- to improve the representation of both natural processes and human systems, including human decision-making and other social science-oriented aspects (e.g., to explore the potential of developing a hybrid modeling system with both AI/ML and traditional modeling components);
- to better quantify uncertainty in future climate projections (e.g., for energy infrastructure design and resilience assessment);
- to make the modeling more efficient computationally (e.g., for downscaling to local information); and
- to study coupled human-Earth system predictability (e.g., to understand if the predictability of extreme events is higher than that for the normal conditions and if model deficiencies decrease the predictability of the coupled system).

These AI/ML applications require customized solutions for domain-specific problems, and they can be achieved only through better collaborations between Earth scientists and AI/ML experts.

Model application to energy security. One key application of the coupled human-earth system modeling capability on DOE's exascale computers is to address science questions relevant to energy security, in the broad sense. With this, the new science derived from Earth observations and model-generated data can be used to achieve broad benefits ranging from informing the design of robust resilient energy infrastructures to risk analysis involving natural disaster impact mitigation to natural resource management and environmental stewardship. BER should work more closely with DOE applied energy programs and Office of Energy Policy and Systems Analysis to assist in the planning of our Nation's energy infrastructure and in the assessment and mitigation of potential damages to, e.g., energy and related infrastructures. In particular, this planning can be assisted by tradeoff and scenario analyses using fully coupled human-Earth system modeling along with exascale computing. For this purpose, the framework widely used in making major observing system decisions would be very valuable: the Observing System Simulation Experiment (OSSE) which is a modeling experiment used to evaluate the value of a new observing system when actual observational data are not available.

ARM and EMSL user facilities. These observing facilities provide the backbone to test and improve models, and they need to keep up with new capabilities (e.g., phased-array radar and a variety of edge computing technologies for ARM). Tighter integration across BER's observing and modeling platforms is also needed. For instance, LASSO should be further expanded by working with modeling groups to develop (or expand) frameworks for data-model integration at even fine resolutions. To expand the user base and help convert data into information and then into knowledge, enhanced data service is needed for data discovery, visualization and animations, and tailored needs of users. For instance, with the expansion of ARM data volume for data sets from instruments such as scanning radars or LASSO simulations, local computing at the ARM Data Center becomes necessary for some users.

Outreach and Partnership. Recognizing the lack of under-represented researchers in the relevant field, DOE's climate and environmental systems research projects and programs should proactively reach out to colleges and universities with a focus on Minority-Serving Institutions and Historically Black Colleges and Universities (e.g., through summer internship, summer school, developing training materials, building modules to apply observational and model data in the classroom). The results from multi-sector dynamics modeling (e.g., on economics, population, land use, and climate drivers for coastal development and engineering) are directly relevant to the study of environmental equity and justice, and hence outreach to relevant communities is needed and collaborations should be pursued.

In the U.S., interagency collaborations (e.g., through the USGCRP) should be strengthened. For instance, the collaboration between ARM and NASA-supported scientists leads to the use of ARM data for the calibration and validation of satellite remote sensing retrievals and data. As another example, further interagency collaborations could be pursued to study the water cycle (e.g., precipitation, snowpack, evaporation, soil moisture, river streamflow, and lake water levels) over the U.S. through the USGCRP's Integrated Water Cycle Group. Besides these interagency collaborations, the coupled human-Earth system modeling capabilities will also allow potential partnerships with the private sector on topics like extreme events under climate change (e.g., relevant to the insurance and reinsurance industry).

Internationally, E3SM has participated in the CMIP6 model intercomparison activities for the IPCC AR6, GCAM has contributed scenarios that drive CMIP5 and CMIP6, and ARM has a close collaboration with the GEWEX Global Atmospheric System Studies Panel in data archive and in organizing a competition of early-career researchers (including graduate students) in using the ARM data for atmospheric process understanding. A new opportunity is the World Climate Research Programme's lighthouse initiative on Digital Earth - a dynamic representation of the Earth system founded on an optimal blend of models and observations. With the development of the E3SM global cloud-permitting model (with a grid spacing of 3 km) for exascale computers, DOE should actively participate in this international activity and take leadership where appropriate. These and other international collaborations can benefit DOE and the Nation, and can be used to continuously monitor the health of the Earth, study the effects of climate change and the state of the oceans and cryosphere, and improve modeling and predictive capabilities around extreme weather events and over heterogeneous or high gradient regions (e.g., urban, coastal).

Email: xubin@arizona.edu; web: https://xzeng.faculty.arizona.edu/

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