Preview of Award 2410910 - Final Annual Project Report

Cover |
Accomplishments |
Products |
Participants/Organizations |
Impacts |
Changes/Problems

Cover

Federal Agency and Organization Element to Which Report is Submitted:	4900
Federal Award or Other Identifying Number Assigned by Agency:	2410910
Project Title:	International Summit to Consider a Special-Purpose Computational System for Frontier Earth System Science and Climate Projection; Urbana, Illinois; Fall-2024
PD/PI Name:	Kelvin K Droegemeier, Principal Investigator
Recipient Organization:	University of Illinois at Urbana-Champaign
Project/Grant Period:	06/15/2024 - 05/31/2025
Reporting Period:	06/15/2024 - 05/31/2025
Submitting Official (if other than PD\PI):	Kelvin K Droegemeier Principal Investigator
Submission Date:	09/03/2025
Signature of Submitting Official (signature shall be submitted in accordance with agency specific instructions)	Kelvin K Droegemeier

Accomplishments

*** What are the major goals of the project?**

The goal of this workshop (hereafter referred to as the summit) was to discuss the practicability of creating a specialized computational system to support frontier Earth system science research and climate projection at the spatial fidelity of today's numerical weather prediction (NWP) models (1 to 3 kilometers between locations in a global mesh at which calculations are made). Such detailed computer simulations using sophisticated global Earth system models (ESMs), integrated with artificial intelligence and machine learning (AI/ML) capabilities, are believed essential for understanding the local impacts of future events such as fine-scale extreme weather, as well as the two-way interactions between such events and larger/global-scale phenomena.

Although others have examined approaches for accommodating fine-scale ESMs run globally, focusing on hardware-software co-design, recommendations largely were not implemented. Additionally, AI/ML had not yet been applied to NWP models and ESMs in the manner they have today, leading to proposed computational frameworks focused principally on traditional physics-based modeling strategies.

The summit took a notably different approach by placing the needs of practitioners – who rely on ESM-derived information for making decisions – as the driving force behind the design framework of a specialized computational system for Earth system science and climate projection. Example application areas include insurance and reinsurance, risk and catastrophe modeling, urban and coastal planning, infrastructure and resilience, energy, agriculture, transportation, communications, recreation, health, and land management. Such needs also motivate the research required to create the computational and modeling framework as well as the pioneering research that would result from it.

Because numerous efforts already are underway internationally to establish kilometer-scale ESMs,[1] addressing issues such as representations of physical processes, computational grids, and data frameworks, *the summit emphasized the other side of the coin: namely, creating a computational environment which would make multi-decade ensemble projections from fine-scale ESMs practicable*. More specifically, the summit sought to address the following question:

Will the evolution of computational systems, as presently envisioned, be sufficient to support large ensembles of kilometer-scale global climate simulations soon enough to help answer key scientific questions, and to support local and regional decision-making regarding environmental change?

The summit addressed additional questions, including but not limited to the following:

- How can challenges of running ESMs on current and future HPC systems best be overcome in hardware and application/system software, especially using AI?
- How can heterogeneities within ESMs, both in terms of the structure of equations being solved and the physical processes they represent, be leveraged to optimize performance in hardware and software?
- How can practitioners and stakeholders best utilize high-resolution information from ESMs, and what features and events need to be captured?
- What are the best approaches for mapping ESMs, now being converted to high spatial resolution, to special-purpose systems (e.g., languages, codes, and components to be used, roles of different organizations)?
- What functional requirements (e.g., computational time, memory, output storage, visualization, analysis) exist for fine-scale global ESMs, their ensembles, and integrative AI to produce meaningful many-decade to century-duration climate projections?
- How does model resolution impact ensemble size and related information for decision making, predictability limit estimation, etc?
- Is a computational system (which might consist of a system of systems), co-designed by scientists and engineers specifically for large ensembles of km-resolution ESM runs that also interacts with AI systems, technically feasible and the best approach to be taken?
- What innovations and research will be required (e.g., chips, interconnect, memory, I/O, operating system, memory hierarchy, networking, compiler, etc) to achieve this capability?
- Can such an effort be completed in five years, and how much would it cost?
- Would such a system be sufficiently stable to support innovative science and long-term global climate projections?
- What would be the effective lifetime of such a system, scientifically and structurally?
- Can the envisioned system be powered solely or mostly by renewable energy sources?

- What alternative technology pathways exist, both immediately and in the short-term (5-10 years), and how could they accelerate progress toward the stretch goal?
- Is it possible or even likely that advances in general-purpose computing capabilities, when coupled with AI, would provide the needed capability by the time a special-purpose computational system could become operational?
- How can the envisioned system be used to better understand interactions of Earth system phenomena across scales, particularly the mutual interactions between fine-scale/extreme weather (e.g., thunderstorms) and the larger/global scale environments in which they form?
- How should fine-scale ESMs applied globally be initialized? Do traditional data assimilation techniques apply?
- What can we learn about atmospheric predictability by running fine-scale ESMs globally?
- What changes are needed in model physics parameterizations to produce reliable and physically realistic solutions at fine scales globally?
- What roles can AI/ML play in fine-scale ESMs applied globally, including for producing ensembles?
- What organizational/administrative structure(s) would be most effective in developing and executing a plan for such a computational system, and what exemplars can be used as role models (e.g., CMIP, ITER, and even complex, multi-national manufacturing activities such as commercial airplanes)?
- How would such an effort be funded, and what organizations would be involved? How could the effort not detract from the necessary continued support of general-purpose computing for research, and also not have deleterious impacts on the research workforce needed to continue performing important climate research?
- What incentives exist for participation in an international initiative, especially by non-government funding organizations? What issues could arise with regard to intellectual property ownership for a system to which multiple organizations contribute proprietary capabilities?
- Would any of these issues inhibit the system from being fully open to international users and its output being made available without restriction? How will the output be shared?
- What would kilometer-scale global climate projections enable for society, and what technological spillover effects could be realized by academia, government, and the private sector that would not occur in the absence of such an effort? How could a special-purpose computational system be operated to most effectively meet both research and operational needs?
- In light of the CHIPS and Science Act of 2022, how would an effort to build a special-purpose computational system positively impact U.S. global competitiveness in microelectronics, AI, climate science, and high-performance computing?
- What educational benefits could be realized from such an effort, and how could it stimulate interest in STEM fields and broaden the participation of traditionally underrepresented groups in a merit-based competitive framework?
- How could such an effort benefit other disciplines?

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[1] Examples include but are not limited to the Earth Virtualization Engines project, Earthworks project, U.S. Department of Energy (DOE) Exascale Earth System Model (E3SM), European Union’s Destination Earth and nextGEMS, Swiss EXCLAIM, and Japan’s NICAM-GLES**.**

*** What was accomplished under these goals and objectives (you must provide information for at least one of the 4 categories below)?**

Major Activities:

1. Consensus on a Computational Environment and Modeling Framework to Address Stakeholder Needs

Participants generally agreed on a two-phase strategy for building a global climate modeling infrastructure capable of delivering high-resolution, stakeholder-relevant information. The first phase focuses on achieving global simulations at ~10 km grid spacing over decadal timeframes (about 10 years), allowing the system to begin capturing natural climate variability and provide meaningful outputs for many decision contexts. This phase assumes rapid advances in computational capabilities and leverages ongoing international modeling efforts.

The second phase targets ~1 km global grid spacing over ~30-year periods to better capture both natural variability and anthropogenic effects. A key architectural innovation in this phase is the development of an ECMWF-like structure for the community—a shared, modular modeling framework capable of evolving with scientific progress. This system would not be fully plug-and-play, but would incorporate sufficient variability (e.g., multiple dynamical cores and physics options) to support ensemble modeling and integrate advances from multiple research groups. Participants emphasized that the envisioned system should support a flexible, hierarchical modeling architecture capable of spanning LES-scale research to coarse-resolution operational runs. A single

modeling framework that can operate across a wide range of resolutions and incorporate AI at various levels—from physical parameterizations to hybrid and fully AI-driven approaches—was seen as a desirable long-term goal.

Additional R&D needs emphasized during summit discussions include process representations not yet adequately resolved even at kilometer scales. These include lateral groundwater flow, cloud microphysics, and aerosol-cloud-radiation interactions. Significant attention must also be paid to improving turbulence parameterizations, shallow and deep convection, and biogeochemical coupling in the ocean. Advancing these capabilities is essential to ensure the physical credibility of next-generation ESMs.

Stakeholder needs are further addressed through the prioritization of use cases (e.g., compound extremes, infrastructure planning, financial risk management), integration of data assimilation and reanalysis capabilities, and development of translation tools that convert raw model output into actionable information. The importance of tailored information delivery—such as return period statistics, probabilistic event characterization, and uncertainty quantification—was emphasized repeatedly, along with the recognition that both expert users and non-experts must be served through expert translators of the science to the practitioners, tiered data interfaces and visualization systems.

2. Key Research Questions to Ensure Reliable Model Results

To produce trusted and decision-relevant outputs, several foundational scientific questions must be addressed. Chief among these is the representation of clouds, precipitation, and feedback processes at km scales, as these directly impact the simulation of extreme events and compound hazards. Improved coupling between atmosphere, ocean, land surface, and ice systems at high resolution is critical, especially given the timescale goals of the initiative.

A recurring theme was the importance of bridging the weather-climate continuum through unified modeling frameworks that can reliably simulate both short-term and long-term phenomena. Advancing subgrid parameterizations, especially for convection and boundary-layer processes, is seen as essential to reduce uncertainty. Participants also identified the need for robust model evaluation frameworks that move beyond traditional skill metrics to assess reliability, reproducibility, and stakeholder relevance. Trust in km-scale model outputs will depend upon rigorous validation using real-time observations and clearly communicated uncertainty bounds. Stakeholders from sectors such as insurance and infrastructure emphasized the need for high-resolution simulations of rare events (e.g., 15-minute precipitation totals, 10,000-year event modeling) to support probabilistic decision-making. Incorporating satellite simulators and standardized test protocols is expected to play a significant role in this validation work.

Another major scientific priority involves the co-evolution of AI and physics-based models. Emulators, surrogate models, and machine learning-assisted parameterizations must be tightly coupled with traditional methods to both accelerate simulations and enhance fidelity. This requires innovative approaches to uncertainty quantification and to characterizing emergent behaviors in hybrid modeling systems.

3. Administrative Structure, Facilities Concept, and Funding Model for a Global Initiative

The summit concluded with a shared understanding that delivering this ambitious vision will require not only scientific and technical innovation, but also a bold rethinking of institutional, organizational, and funding structures. There was widespread support for forming a globally coordinated framework akin to ECMWF, but tailored to the unique demands of km-scale modeling and open science. This would involve standing up a core international facility—or distributed network of facilities—that brings together

computing infrastructure, modeling expertise, stakeholder engagement teams, and translational workforce capacity.

Importantly, participants rejected the notion of business-as-usual administration. Instead, the group advocated for a flexible, adaptive governance model that empowers global participation, facilitates co-development, and encourages innovation without fragmentation. Special emphasis was placed on democratization, particularly involving scientists and institutions from the Global South. Structures must be intentionally inclusive of under-resourced communities and build capacity where needed.

Regarding funding, the discussion envisioned a multi-source model that begins with rapid mobilization of philanthropic and non-governmental resources to launch the initiative, followed by sustained public sector investment. The idea is to create a catalytic “super-model” effort that can initially augment existing national capabilities but eventually provide operational and scientific value far beyond what individual countries could achieve alone.

Support for such a model will depend on the articulation of a compelling narrative for multiple audiences—governments, industry, foundations, and the public. This includes not only the scientific benefits of km-scale modeling, but its transformative impacts on sectors like agriculture, energy, disaster preparedness, finance, and public health. Messaging should emphasize the creation of a community of practice, and not simply a technical system.

Specific Objectives:

Significant Results:

Key outcomes or Other achievements:

The final discussions outlined a set of priorities to translate summit momentum into action. These include:

- Finalizing the two-phase modeling framework and its stakeholder-informed performance goals.
- Establishing working groups to develop a coordinated research agenda, data management strategies, and use-case translation pathways.
- Designing an administrative prototype for a global facility or consortium, with active outreach to existing entities like WCRP and Digital Earth.
- Developing strategic funding pitches to philanthropic and government agencies, using high-value use cases to illustrate impact.
- Creating pathways for inclusive participation, especially for under-resourced scientists and regions, through education, workforce development, and co-leadership roles.
- Initiating a communication strategy focused on the value proposition of km-scale modeling to society, emphasizing both climate resilience and economic opportunity.

1. Post-Summit Communication

A key to maintaining momentum developed during the summit is continuous communication with the organizations involved, the addition of other organizations, creating a leadership structure and building and executing a strategic plan, and establishing increasingly strong linkages with the stakeholder/practitioner community. Efforts are underway on each of these topics.

*** What opportunities for training and professional development has the project provided?**

The summit generated significant broader impacts by focusing on transformational climate modeling in service to society, and by providing mechanisms globally to participate in the summit and utilize its archived products. Through its comprehensive and forward-looking approach, the summit brought together a diverse, interdisciplinary community to co-develop a vision for next-generation, fine-scale climate information systems. By framing climate modeling as a global public good, the project promoted democratization of access, particularly for under-resourced regions and communities that are often most vulnerable to climate change yet lack adequate decision-support tools.

*** Have the results been disseminated to communities of interest? If so, please provide details.**

1. Informal Publications

Droegemeier, K.K., 2024. Working Toward a Computational Framework to Support Earth System Science and Climate Projection. The Download, National Center for Supercomputing Applications, University of Illinois Urbana-Champaign. Available at https://www.ncsa.illinois.edu/kelvin-k-droegemeier-on-working-toward-a-computational-framework-to-support-earth-system-science-and-climate-projection/.

2. Invited Publications

Droegemeier, K.K. and Co-authors, 2025: A global community approach for transforming Earth system science and climate projection. In *Pathways to Sustainability: Collaborative Solutions for a Resilient Future*. D. Killeen, D. Wuebbles, and J. Lane Eds. University of Illinois Press, 285 pp.

3. Planned Publications

The summit Planning Committee intends to publish a summary of the summit in an archive journal.

4. Archived Materials from Summit

All videos and presentation slides from the summit are archived on the University of Illinois Urbana-Champaign Media Space system (https://mediaspace.illinois.edu/).

Products

Books

Book Chapters

Kelvin K. Droegemeier, Francina Dominguez, Barb Helland, L. Ruby Leung, Maria J. Molina, Andreas F. Prein, Dan Reed, John Shalf, Bjorn Stevens, John Towns (2025). A global community approach for transforming Earth system science and climate projection. *Pathways to Sustainability* Timothy L. Killeen, Donald J. Wuebbles, Jason E. Lane. University of Illinois Press. Urbana, IL; Chicago, IL; Springfield, IL. 201. Status = PUBLISHED; Acknowledgement of Federal Support = Yes ; Peer Reviewed = No ; ISBN: 9780252089077.

Inventions

Journals or Juried Conference Papers

View all journal publications currently available in the NSF Public Access Repository for this award.

The results in the NSF Public Access Repository will include a comprehensive listing of all journal publications recorded to date that are associated with this award.

Licenses

Other Conference Presentations / Papers

Other Products

View all workshop reports currently available in the NSF Public Access Repository for this award.

The results in the NSF Public Access Repository will include a comprehensive listing of all workshop report publications recorded to date that are associated with this award.

Other Publications

Kelvin K. Droegemeier (2024). *Working Toward a Computational Framework to Support Earth System Science and Climate Projection*. Overview of the summit funded by the NSF grant to be held later in the year.. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Patent Applications

Technologies or Techniques

Thesis/Dissertations

Websites or Other Internet Sites

Participants/Organizations

What individuals have worked on the project?

Name	Most Senior Project Role	Nearest Person Month Worked
Droegemeier, Kelvin	PD/PI	10
Bretherton, Chris	Other Professional	2
Brokish, Jean	Other Professional	2
Dagon, Katie	Other Professional	2
Dominguez, Francina	Other Professional	2
Ford, Trent	Other Professional	2
Fowler, Hayley	Other Professional	2
Gall, Jeff	Other Professional	2
Gentine, Pierre	Other Professional	2
Hack, Jim	Other Professional	2
Hacker, Josh	Other Professional	2
Heistand, Glenn	Other Professional	2
Helland, Barb	Other Professional	2
Hoefler, Torsten	Other Professional	2
Hurrell, Jim	Other Professional	2
Jablonowski, Christiane	Other Professional	2
Kaplan, Larry	Other Professional	2
Kirk-Davidoff, Dan	Other Professional	2
Leung, Ruby	Other Professional	2
Makra, Edith	Other Professional	2
McGovern, Amy	Other Professional	2

Name	Most Senior Project Role	Nearest Person Month Worked
Messmer, Peter	Other Professional	2
Molina, Maria	Other Professional	2
Pan, Ming	Other Professional	2
Petch, Jon	Other Professional	2
Prein, Andreas	Other Professional	2
Qualters, Irene	Other Professional	2
Reed, Dan	Other Professional	2
Satoh, Masaki	Other Professional	2
Schneider, Tapio	Other Professional	2
Schulte, Mike	Other Professional	2
Shalf, John	Other Professional	2
Stevens, Bjorn	Other Professional	2
Suarez Garcia, Maria	Other Professional	2
Towns, John	Other Professional	2
Wehner, Michael	Other Professional	2
Young, Cliff	Other Professional	2
Zanna, Laure	Other Professional	2

Full details of individuals who have worked on the project:

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Most Senior Project Role: PD/PI
Nearest Person Month Worked: 10

Contribution to the Project: Principal Investigator and Project Director

Funding Support: Institutional contribution

Change in active other support: No

International Collaboration: No
International Travel: No

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Nearest Person Month Worked: 2

Contribution to the Project: Primary workshop discussant

Funding Support: Travel to workshop provided by the NSF grant

International Collaboration: No
International Travel: No

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Nearest Person Month Worked: 2

Contribution to the Project: Primary workshop discussant

Funding Support: Travel to workshop provided by the NSF grant

International Collaboration: No
International Travel: No

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Nearest Person Month Worked: 2

Contribution to the Project: Primary workshop discussant

Funding Support: Travel to workshop provided by the NSF grant

International Collaboration: No
International Travel: No

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Nearest Person Month Worked: 2

Contribution to the Project: Member of Planning Committee

Funding Support: Local participant

International Collaboration: No
International Travel: No

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Nearest Person Month Worked: 2

Contribution to the Project: Primary workshop discussant

Funding Support: Local participant

International Collaboration: No
International Travel: No

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Nearest Person Month Worked: 2

Contribution to the Project: Primary workshop discussant

Funding Support: Travel to workshop provided by the NSF grant

International Collaboration: Yes, United Kingdom
International Travel: No

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Contribution to the Project: Primary workshop discussant

Funding Support: Travel to workshop provided by the NSF grant

International Collaboration: No
International Travel: No

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Contribution to the Project: Primary workshop discussant

Funding Support: Travel to workshop provided by the NSF grant

International Collaboration: No
International Travel: No

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Contribution to the Project: Primary workshop discussant

Funding Support: Travel to workshop provided by the NSF grant

International Collaboration: No
International Travel: No

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Nearest Person Month Worked: 2

Contribution to the Project: Primary workshop discussant

Funding Support: Travel to workshop provided by the NSF grant

International Collaboration: No
International Travel: No

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Contribution to the Project: Primary workshop discussant

Funding Support: Local participant

International Collaboration: No
International Travel: No

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Nearest Person Month Worked: 2

Contribution to the Project: Member of Planning Committee

Funding Support: Travel to workshop provided by the NSF grant

International Collaboration: No
International Travel: No

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Nearest Person Month Worked: 2

Contribution to the Project: Primary workshop discussant

Funding Support: Travel to workshop provided by the NSF grant

International Collaboration: Yes, Switzerland
International Travel: No

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Contribution to the Project: Primary workshop discussant

Funding Support: Travel to workshop provided by the NSF grant

International Collaboration: No
International Travel: No

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Contribution to the Project: Primary workshop discussant

Funding Support: Travel to workshop provided by the NSF grant

International Collaboration: No
International Travel: No

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Contribution to the Project: Primary workshop discussant

Funding Support: Travel to workshop provided by the NSF grant

International Collaboration: No
International Travel: No

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Nearest Person Month Worked: 2

Contribution to the Project: Primary workshop discussant

Funding Support: Travel to workshop provided by the NSF grant

International Collaboration: No
International Travel: No

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Contribution to the Project: Member of Planning Committee

Funding Support: Travel to workshop provided by the NSF grant

International Collaboration: No
International Travel: No

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Contribution to the Project: Primary workshop discussant

Funding Support: Travel to workshop provided by the NSF grant

International Collaboration: No
International Travel: No

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Nearest Person Month Worked: 2

Contribution to the Project: Primary workshop discussant

Funding Support: Travel to workshop provided by the NSF grant

International Collaboration: No
International Travel: No

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Nearest Person Month Worked: 2

Contribution to the Project: Primary workshop discussant

Funding Support: Travel to workshop provided by the NSF grant

International Collaboration: No
International Travel: No

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Contribution to the Project: Member of Planning Committee

Funding Support: Travel to workshop provided by the NSF grant

International Collaboration: No
International Travel: No

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Contribution to the Project: Primary workshop discussant

Funding Support: Travel to workshop provided by the NSF grant

International Collaboration: No
International Travel: No

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Contribution to the Project: Primary workshop discussant

Funding Support: Travel to workshop provided by the NSF grant

International Collaboration: No
International Travel: No

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Contribution to the Project: Member of Planning Committee

Funding Support: Travel to workshop provided by the NSF grant

International Collaboration: Yes, Switzerland
International Travel: No

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Contribution to the Project: Primary workshop discussant

Funding Support: Travel to workshop provided by the NSF grant

International Collaboration: No
International Travel: No

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Nearest Person Month Worked: 2

Contribution to the Project: Member of Planning Committee

Funding Support: Travel to workshop provided by the NSF grant

International Collaboration: No
International Travel: No

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Nearest Person Month Worked: 2

Contribution to the Project: Primary workshop discussant

Funding Support: Travel to workshop provided by the NSF grant

International Collaboration: Yes, Japan
International Travel: No

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Nearest Person Month Worked: 2

Contribution to the Project: Primary workshop discussant

Funding Support: Travel to workshop provided by the NSF grant

International Collaboration: No
International Travel: No

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Contribution to the Project: Primary workshop discussant

Funding Support: Travel to workshop provided by the NSF grant

International Collaboration: No
International Travel: No

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Nearest Person Month Worked: 2

Contribution to the Project: Member of Planning Committee

Funding Support: Travel to workshop provided by the NSF grant

International Collaboration: No
International Travel: No

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Contribution to the Project: Member of Planning Committee

Funding Support: Travel to workshop provided by the NSF grant

International Collaboration: Yes, Germany
International Travel: No

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Contribution to the Project: Primary workshop discussant

Funding Support: Travel to workshop provided by the NSF grant

International Collaboration: Yes, Germany
International Travel: No

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Most Senior Project Role: Other Professional
Nearest Person Month Worked: 2

Contribution to the Project: Member of Planning Committee

Funding Support: Local participant

International Collaboration: No
International Travel: No

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Nearest Person Month Worked: 2

Contribution to the Project: Primary workshop discussant

Funding Support: Travel to workshop provided by the NSF grant

International Collaboration: No
International Travel: No

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Contribution to the Project: Primary workshop discussant

Funding Support: Travel to workshop provided by the NSF grant

International Collaboration: No
International Travel: No

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Nearest Person Month Worked: 2

Contribution to the Project: Primary workshop discussant

Funding Support: Travel to workshop provided by the NSF grant

International Collaboration: No
International Travel: No

What other organizations have been involved as partners?
Nothing to report.

Were other collaborators or contacts involved? If so, please provide details.

the summit was organized by a 10-member Planning Committee. In addition to the Planning Committee, a group of 29 individuals (19 men and 10 women) composed the Nucleus Team, the role of which was to serve as the primary discussants during the summit as well as to give presentations and co-lead breakout sessions. Nucleus Team members were drawn internationally from a broad array of academic, corporate, and non-profit organizations representing the four organizing themes of the summit.

Impacts

What is the impact on the development of the principal discipline(s) of the project?

Structured around plenary sessions, breakout discussions, and networking opportunities, the summit addressed three foundational challenges: defining a scientifically credible and societally relevant vision; identifying the research, data, and computational infrastructure needed to implement the vision; and exploring new models for governance and funding. Discussions emphasized the urgent need for a global modeling framework capable of kilometer-scale resolution built on a modular computational architecture, open data principles, and co-designed with stakeholders. Participants endorsed a two-phase approach: an initial focus on 10 km-resolution global modeling over a decadal timescale, followed by a second phase targeting 1 km resolution and 30- to 50-year simulations to capture both natural variability and anthropogenic signals.

Breakout sessions yielded clear priorities for action, including better integration of physical and AI-based models, creation of a specialized distributed but coordinated computational ecosystem, development of standardized model outputs and validation frameworks, and design of a stakeholder-driven translational infrastructure. The summit also highlighted the importance of governance mechanisms that ensure inclusivity, agility, and sustained investment. Cross-cutting themes included workforce development, open science, and the urgent need to engage philanthropic, public, and private funding partners.

What is the impact on other disciplines?

The summit was built around four Organizing Themes: (1) Practitioners and Stakeholders; (2) Earth System Models; (3) Computational Systems (Requirements for System Architecture and Operational Software); and (4) Artificial Intelligence and Machine Learning. To best prepare summit participants in advance and thus maximize the value of time spent in person during the summit, Planning Committee members led several Pre-Summit Intensives (PSIs) on each of the four themes during spring and summer, 2024. Each PSI had approximately two dozen participants, chosen by the PSI chairs/co-chairs. Several questions were provided in advance of each meeting and read-ahead summaries prepared and placed on the summit website.

The first set of five breakout sessions dealt with the following topics: (1) A New Approach for the International Community; (2) Crosscutting Topics; (3) Earth System Models and AI/ML; (4) Computational Systems; and (5) Practitioners, End-Users and Stakeholders. The discussions spanned scientific, technical, organizational, and stakeholder-oriented themes, offering a multifaceted roadmap toward realizing the proposed vision.

Breakout Group #1 focused on international collaboration and a novel approach to mobilizing global expertise and infrastructure. Participants stressed the need for a shared vision that is clearly articulated and strategically framed to galvanize political and financial support. Central to this vision is a commitment to democratizing access to high-resolution climate information, advancing model development (e.g., 1km resolution), and ensuring appropriate engagement across geographic regions and societal sectors. The group underscored the importance of designing a flexible institutional framework that can support co-development, inclusive governance, and rapid innovation without being hindered by existing bureaucratic structures.

Breakout Group #2 addressed several cross-cutting issues, including model development, stakeholder needs, communication strategies, and research priorities. The group advocated for robust validation frameworks, stakeholder-driven performance benchmarks, and the incorporation of human and ecological dimensions into modeling systems. A recurring theme was the necessity of “climate interpreters”—human or AI intermediaries capable of translating model output into actionable information for a range of users. The group also emphasized the need for compelling narratives and demonstrable societal benefits to secure funding and political will. Specific focus on extreme and compound events such as droughts, heat waves, wildfires, and precipitation – as well as longer-term information about water availability – were highlighted as focal points for advancing both science and public value.

Breakout Group #3 examined the integration of Earth system models with artificial intelligence and machine learning (AI/ML). The group emphasized that km-scale models must be nested within a hierarchy of modeling frameworks to ensure scalability and robustness. AI tools were seen as instrumental for model calibration, emulation, and data assimilation, especially over seasonal to decadal timescales. Participants discussed the need for flexible, modular modeling platforms that support diverse grid resolutions and leverage high-level programming languages to future-proof the system and attract early-career talent. The group also identified critical challenges in computational infrastructure, particularly in terms of data storage, model tuning, and the co-design of software and hardware systems. The summit highlighted challenges related to programming language choices and code portability. Although many legacy models use Fortran, a growing shift exists toward C++, Python, and Julia to enable cross-platform flexibility. Porting large codes like CESM to GPU-accelerated Python was estimated to require 100 FTEs. Frameworks such as Kokkos and GT4Py were recommended to facilitate this transition.

Breakout Group #4 concentrated on the computational infrastructure required to support the initiative. Participants agreed that although the goal of 1km resolution models is scientifically justified, the computational and data workflows to support them must be explicitly mapped and optimized. They highlighted the importance of understanding software requirements and leveraging existing tools where appropriate, but also acknowledged the likely need for novel solutions tailored to AI-augmented modeling. The group discussed the distinct needs of physical and AI-driven models and the necessity of building systems capable of supporting both. Workflow design, including rapid response capabilities for stakeholder “what-if” scenarios, was identified as critical to the success and utility of the platform.

Breakout Group #5 focused on the scientific, technological, and human capital investments needed to build a next-generation climate modeling system. The group proposed that km-scale models should deliver credible forecasts from days to decades, with improved simulation of precipitation, clouds, and extremes. To achieve this, addressing unresolved processes like boundary-layer clouds, microphysics, and biogeochemical cycles is essential. The group also discussed the need for robust evaluation tools and standardization of outputs rather than internal APIs. A key long-term goal is to design an open, accessible modeling environment that integrates storage and compute capabilities while supporting workforce development. Several participants emphasized the importance of locating compute resources close to data storage. The Japanese strategy of allowing remote access to co-located data, and GFDL’s practice of cloud-based coarse-grained sharing, were highlighted as promising models. Online diagnostics, real-time compression, and encoding/decoding optimization were identified as necessary to manage the vast output from fine-scale simulations. The group acknowledged the tension between unifying around a single modeling framework and enabling innovation across diverse modeling platforms.

Collectively, these breakout sessions laid the groundwork for a transformative international initiative that aspires not only to push the boundaries of Earth system modeling but also to deliver climate information that is scientifically credible, societally meaningful, and globally inclusive. Participants stressed that success hinges on a bold, coherent vision, sustained investment in human and computational resources, and transparent, adaptive governance structures capable of evolving with scientific and societal needs.

What is the impact on the development of human resources?

The issue of workforce development was intergrated throughout all four pillars of the summit in areas of atmospheric science, computer and computational science, risk and decision-making, social and behavioral science, and public policy. Traditionally

these areas have operated somewhat separately, and in the context of atmospheric science, weather and climate have largely been distinct. WIth the ESM capabilities discussed at the summit, the weather-climate interface is becoming blurred, with ESMs run globally at fine resolution operating similar to current numerical weather preediction models. Workforce development must occur not only in traditional institutions of higher education, but also in research centers and operational settings, including in the private sector, where usesr of environmental infromation must have skills in business, risk, decision-making, and the ability to influence public policy. The summit addressed all of these areas in a comprehensive, integrated fashion, the centerpiece of which is a specialized computational system that brings all sectors together to address significant challenges of practical importance to society.

What was the impact on teaching and educational experiences?

Summit participation took multiple forms. First, in-person participation was by invitation-only, given budgetary constraints. Invited individuals paid their own expenses, apart from Nucleus Team and Planning Committee members, who were funded by the NSF grant. Invitees who could not participate in person were allowed to participate as Zoom panelists (i.e., full interactivity). The second form of participation was by invitation as well, but only remotely as Zoom panelists. The Final form involved global participation via a free YouTube web stream designed especially for students and teachers to engage in summit topics. All participants were required to register.

Considerable effort was directed toward maximizing the breadth of participants both in the US and globally. Promotional material was sent to nearly 100 organizations, ranging from US Federal agencies, research centers (e.g., Climate Adaptation Science Centers, National Center for Atmospheric Research, NOAA organizations) to academic institutions, disciplinary professional societies, and organizations representing women, minorities, and traditionally under-resourced institutions.

Internationally, promotional materials were sent to operational and research weather and climate centers, UN organizations, and academic and independent research institutions. Table 2 shows the demographics of invitations to individual persons and their participation, as well as YouTube participants. The summit was announced via a press release and on the NCSA website (https://www.ncsa.illinois.edu/international-summit-seeks-to-harness-supercomputing-power-for-climate-decision-making/), and the PI wrote a promotional article as part of the NCSA “Download” series (https://www.ncsa.illinois.edu/kelvin-k-droegemeier-on-working-toward-a-computational-framework-to-support-earth-system-science-and-climate-projection/). These links were included in invitations.

What is the impact on physical resources that form infrastructure?

A key focus of the summit was the computational infrastructure required to support kilometer-scale Earth system models run globally. Participants agreed that although the goal of 1km resolution models is scientifically justified, the computational and data workflows to support them must be explicitly mapped and optimized. They highlighted the importance of understanding software requirements and leveraging existing tools where appropriate, but also acknowledged the likely need for novel solutions tailored to AI-augmented modeling. The group discussed the distinct needs of physical and AI-driven models and the necessity of building systems capable of supporting both. Workflow design, including rapid response capabilities for stakeholder “what-if” scenarios, was identified as critical to the success and utility of the platform.

Discussions from the first breakout session illustrated the need for emphasis on additional topics for the second breakout session, notably (1) Use Cases; (2) A Research and Development (R&D) Agenda; and (3) Data and Tools.

Breakout Group #1 centered its discussion on defining high-impact use cases and variables necessary for climate-informed decision-making. The group emphasized the critical importance of stakeholder trust in model outputs and highlighted the need to generate reliable, actionable projections of short-duration, extreme weather events—particularly those relevant to engineering design, insurance, agriculture, and municipal infrastructure planning. Participants pointed to specific requirements, such as the ability to simulate 10-, 100-, and 500-year return period events at high spatial and temporal resolution, and stressed the need to tailor products to varying stakeholder needs (e.g., hourly forecasts for financial markets, seasonal precipitation for agriculture). Complex compound events—like heat following windstorms or droughts coinciding with pest outbreaks—were identified as high-priority phenomena requiring improved simulation capabilities. The group also called for integrating data assimilation, probabilistic outputs, and rigorous uncertainty characterization to build trust across user communities.

Breakout Group #2 focused on the research and development agenda needed to build km-scale models capable of reliable seasonal to decadal climate projections. The group prioritized advancing the physical realism of models, particularly in terms of precipitation processes, cloud feedbacks, and extreme event simulation. A major objective is to enable forecasts across

timescales—from weather to climate—with a unified modeling framework. The group also highlighted technical challenges, including evaluating coupling schemes at 1km resolution and representing land surface processes accurately. Key recommendations included focusing on climate feedbacks, using satellite simulators for model evaluation, and standardizing model outputs and test protocols rather than APIs. Investment in human expertise—especially in subgrid parameterization—was seen as critical to reducing uncertainty and sustaining innovation.

Breakout Group #3 addressed the design of data systems and analytical tools to support the climate modeling framework. The group emphasized that data infrastructure must support reproducibility, uncertainty quantification, provenance tracking, and explainability of results. They advocated for integrating compute resources close to data to accommodate the massive size of climate model output and to avoid unsustainable data transfer practices. A tiered access and governance model was proposed to balance equity, agility, and operational needs, with attention to differing user requirements—from researchers to policymakers. Notably, participants called for the establishment of “climate interpreters” who can help translate complex outputs into meaningful guidance for diverse users. They underscored that many consumers need synthesized information rather than raw data, and that interfaces should be stratified to reflect varying levels of expertise and use cases.

Taken together, the second set of breakout discussions advanced a more refined and operationally grounded vision for the climate modeling initiative. Although the groups explored different facets—from model physics and computational tools to governance and stakeholder applications—they converged on key principles: stakeholder-driven design, scientific rigor, operational agility, democratization of access, and global collaboration. The outcomes offer a comprehensive framework for aligning innovative climate science with the urgent needs of society.

What is the impact on institutional resources that form infrastructure?

Institutional resources already exist to support the use of Earth system models. However, if a specialized computational system is developed on which such models will be run globally at fine resolution, additional resources may be needed to handle the associated massive output files produced. See Breakout Gruop #3 discussoin.

What is the impact on information resources that form infrastructure?

The summit \addressed technical challenges such as computational scalability, coupling of Earth system components, and the integration of AI/ML with physics-based modeling. Some advocated for modular, interoperable platforms that could evolve over time, while others emphasized the need to ensure that emerging hybrid models maintain transparency and trust. Concerns were raised about the massive data volumes produced by high-resolution simulations, and a shared recognition emerged that next-generation data services must prioritize discoverability, accessibility, and usability for both expert and non-expert users.

What is the impact on technology transfer?

A strong call was made to create a common framework or vision that could unify international and cross-agency efforts, with several participants referencing existing initiatives such as Earth Virtualization Engines (EVE), Destination Earth (DestinE), and DOE’s E3SM. These included recommendations to standardize terminology, share best practices in model development and data dissemination, and promote open, reproducible science. Many contributors stressed the importance of defining meaningful benchmarks and metrics for evaluating model performance—beyond conventional accuracy scores—to better reflect the practical utility of outputs for downstream users.

What is the impact on society beyond science and technology?

The summit assembled individuals from local government, agriculture, reinsurance, and infrastructure to explore how fine-scale ESM/AI information can directly support decision-making across sectors. THese are but a few of the important sectors of society which depend upon environmental information for making critical decisions.

Edith Makra (Metropolitan Mayors Caucus) emphasized the importance of localized climate data for driving regional collaboration on sustainability and resilience planning. In the Chicago metropolitan area, where over 9 million residents span multiple jurisdictions, municipalities are leveraging consensus frameworks like the Greenest Region Compact and localized risk assessments to inform climate action. She underscored the urgent need for data-informed infrastructure investments,

citing the $1.45 billion alternative water source initiative in Joliet as an example of planning shaped by groundwater modeling and regional hydrologic trends.

From an agricultural perspective, Jean Brokish (American Farmland Trust) highlighted the operational and strategic value of climate data across a range of timescales. Farmers make daily to decadal decisions that depend on understanding precipitation patterns, soil moisture, crop suitability, and market infrastructure. Climate information, when translated effectively, can support field-level decisions like irrigation and tillage, help reduce risks to farm labor, and inform longer-term choices around crop rotations and water management infrastructure. She illustrated how changes in precipitation timing and intensity are already constraining spring planting windows in the Midwest and suggested that smart climate-informed tools could help optimize cover crop management, nutrient loss reduction, and farm profitability.

Jeff Gall (RenaissanceRe Risk Sciences) brought a financial and risk analytics lens to the conversation, pointing to the growing demand within the insurance and reinsurance sectors for scientifically-grounded, globally-consistent, and high-resolution hazard simulations. He explained that traditional catastrophe models often simulate one peril-region combination at a time, missing key correlations across regions. In contrast, global Earth system models can simulate simultaneous peril events—such as hurricanes in the U.S., typhoons in Asia, and flooding in Europe—enabling the assessment of interdependencies that are crucial for pricing risk and managing capital exposure. Gall also described the potential of high-resolution modeling for seasonal forecasting, real-time event response, and climate risk quantification, all of which are critical to narrowing the global insurance gap.

Rounding out the session, John England (U.S. Army Corps of Engineers) underscored the necessity of modernizing the estimation of extreme precipitation—known as Probable Maximum Precipitation (PMP)—for critical infrastructure such as dams and levees. Current methods are outdated. England advocated for a phased transition to model-based PMP estimation using kilometer-scale Earth system simulations that can account for uncertainty and evolving hydrologic extremes. He highlighted the benefits of model-based approaches for site-specific safety evaluations and infrastructure design, emphasizing that such methods could become standard within the next decade if supported by sustained research and interagency collaboration.

Collectively, the panel presentations revealed a clear and urgent need across sectors for high-resolution, decision-ready climate information. Practitioners seek not only better data, but also more interpretable, timely, and actionable insights that reflect the scale and complexity of their operations. The session underscored the importance of aligning advances in Earth system modeling with the practical requirements of users on the ground—municipal leaders, farmers, insurers, and engineers alike—through sustained partnerships, iterative tool development, and clear communication of risk and uncertainty.

What percentage of the award's budget was spent in a foreign country?

None. All grant funds were expended in the United States, including those used to support foreign participants.

Changes/Problems

Changes in approach and reason for change

None.

Actual or Anticipated problems or delays and actions or plans to resolve them

None.

Changes that have a significant impact on expenditures

None.

Significant changes in use or care of human subjects

N/A

Significant changes in use or care of vertebrate animals

N/A

Significant changes in use or care of biohazards

N/A

Change in primary performance site location

No.