Report of the SIAM Convening on Climate Science, Sustainability, and Clean Energy

October 10-12, 2022
Tysons, Virginia

Society for Industrial and Applied Mathematics

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Report of the *SIAM Convening on Climate Science, Sustainability, and Clean Energy*

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SIAM Convening on Climate Science, Sustainability, and Clean Energy

The Society for Industrial and Applied Mathematics (SIAM) hosted a 3-day workshop on October 10-12, 2022 with a broad group of researchers and practitioners from various disciplines and from a variety of institutions and companies around the general theme of climate science, sustainability, and clean energy. The **SIAM Convening on Climate Science, Sustainability, and Clean Energy** engaged the scientific community in the identification and articulation of emerging research needs related to these areas in order to explore what foundational long-term research and plans are needed over the next decade, and to give focused input to the National Science Foundation and other federal research and development agencies.

Given that robust and active support of research and education is necessary to anticipate future conditions, accelerate clean energy innovations, and increase the resilience of the United States, the SIAM Convening on Climate Science, Sustainability, and Clean Energy had as goals to: (i) gain a better understanding of the challenges and problems affecting research innovation and translation gleaned from discussions across the various sectors and communities; (ii) provide input and recommendations for addressing the challenges and opportunities identified; and (iii) identify mechanisms to encourage the growth and health of the research workforce.

The steering and planning committee of this "scoping workshop" consisted of the Principal Investigator and nine subject matter experts from a variety of disciplines, with the support of a liaison from Knowinnovation (KI) who guided the design and planning process, and a project assistant from SIAM. For the workshop, KI provided a team of professionals who specialize in guiding and accelerating academic, scientific, and interdisciplinary innovation to facilitate the discussions and the generation of ideas.

Discussions were organized around **six main goal areas:**

i. Advance Scientific Knowledge
ii. Anticipate Future Conditions
iii. Accelerate Clean Energy Innovations
iv. Promote Sustainable Practices
v. Increase Climate Change Resilience
vi. Increase Outreach/Broader Impacts

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Workshop Structure and Output

The SIAM Convening on Climate Science, Sustainability, and Clean Energy took place over the course of three days. This scoping workshop was conducted as follows.

Day 1: Participants began the workshop by getting to know the people and expertise in the room through a series of orientation activities. Participants then began a clarification process of question finding. Discussions were organized around the six main goal areas listed above.

Participants discussed and captured important new questions within these areas around the challenge of taking ambitious, interdisciplinary leaps towards net zero emissions, sustainability, climate change mitigation and adaptation, food security, and climate equity and justice.

Participants then clustered, sorted, and organized the questions and chose the areas in which they would like to work further.

By the end of Day 1, participants had shifted from question finding to solution finding, and began coming up with approaches and recommendations to the different question areas that had been organized.

Participants reviewing "WIGBI" (Wouldn't It Be Great If) ideas.

Day 2: Participants opened Day 2 by voting on the most exciting and important recommendations and approaches identified in Day 1. Participants then formed groups around the most important recommendations and went through a process of developing those ideas for the community to better understand what they entailed.

After this development process, the participants formed writing teams for their final recommendations to be included in the report. Teams had the rest of Day 2 to write and gather feedback on their process.

Day 3: Participants spent the morning of the last day working with their writing teams and finalizing their presentations. The teams gave oral presentations with their final recommendations to the group. They also continued working on their team reports; these are included in this document.

Foreground: Jody Reimer, Guang Lin, Oliver Dunbar, Alice Nadeau, Annalisa Quaini, Alan Hastings, Tracy Rouleau (hidden), and Gerardo Ruiz-Mercado working on their team's recommendation.

There were many ideas brought forth by the participants at the workshop. Several of these ideas were relevant in the context of the workshop objectives but did not generate a critical mass for further development. The convening ultimately resulted in **nine recommendations** which were titled as follows:

1) A Paradigm for Digital Twins to Safeguard the Planet
2) What Happens in the Arctic Does Not Stay in the Arctic
3) Transforming Education to Address Complex Futures
4) Extreme Learning
5) The End of Fossil Fuels
6) ACED: Accelerated Circular Economy Development
7) Sustainable Smart Water Systems (Sustainable Water Grid)
8) Unraveling the Climate Vulnerability Web: Integration of Physical, Biological, Human Social, and Economic Models in Time and Space
9) Change the Conversation at the Local Level

Following the close of the workshop, a subset of the original participants joined with the

Steering Committee to form the Synthesis Report Committee. The presentation slides, recorded presentations, one-page summaries of the recommendations, and this document are all available at the SIAM website www.siam.org.

In all, there were 58 researchers and professionals from the range of disciplines and fields that contribute to and are involved in clean energy, sustainability, and climate science research that participated in this effort. Half of the participants were mathematical scientists, one quarter were engineers, 15% were physical and computer scientists, 5% were atmospheric and geoscientists, and 7% were social and economic scientists. Of these, 62% work in academia, 20.5% in government, 14% in the private sector, and 3.5% in the non-profit sector. One quarter of the participants were early career professionals, 14% were mid-career, and 60% were senior. One third of the participants were women. Two-thirds of the participants identified as white, 14% as Asian/Asian American, and 10% as African American/Black or Native American; 12% identified as Hispanic. A list of the participants can be found at the end of this report in the Convening Participants section.

Convening participants standing outside the meeting space in Tysons Corner, VA.

Summary of Recommendations

There were nine recommendations that emerged from the SIAM Convening on Climate Science, Sustainability, and Clean Energy. These spanned both specific and broad research thrusts that identified various objectives for the methodologies for climate science, engineering solutions towards sustainable solutions to mitigate the consequences of climate change, using social science to help design effective solutions and integrate community feedback, and educating the workforce to support these directions. Listed below is an overview of the recommendations and more details are given in the Convening Recommendations section of this report.

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1. **A Paradigm for Digital Twins to Safeguard the Planet**
   Develop a multi-fidelity, scalable, long-lived open-source platform which consists of protocols, such as quantification and analysis of dynamic uncertainty, that enables systematic analysis of Earth system processes. From this platform, scientists will be able to build problem-specific digital twins. The problem-specific digital twins would continuously adapt as new data is ingested; detect changes in the climate system; measure response to climate mitigation actions; integrate scientific understanding; inform policy decisions; and reduce risk by being uncertainty-aware.

2. **What Happens in the Arctic Does Not Stay in the Arctic**
   From micro to macro in the Arctic climate system. Understanding signature indicators of planetary warming – the loss of sea ice and thawing of permafrost – at the micro level and building up from there will help to make better models and predictions of what's happening in the Arctic and enable us to better understand and respond to the cascading effects experienced both in the United States and globally. The small-scale effects that add up to control the larger scale mechanisms are not understood at the physical level for models in the Arctic. Multiscale hierarchical modeling offers an approach through the development of complex cross-scale models to transfer the critical information from microscales to the macro behavior. Upscaling can be physics-informed and data-driven where possible but may rest on mathematical constructs when the physics is not yet determined, and experimental data are not available.

3. **Transforming Education to Address Complex Futures**
   The world is facing challenges of increasing complexity at an accelerating pace. Mathematics, modeling, data science, and systems analysis are central to researching and developing solutions for complex problems. However, today's students often find it difficult to place coursework into a broader context and synthesize subject areas. A collaborative approach to curricula, classes, and pedagogy should be designed to cross boundaries among STEM, social science, and other disciplines and graduate thinkers who can contribute professionally and personally to solutions for society's Grand Challenges (e.g., climate, human health, food security, national security).

4. **Extreme Learning**
   Extreme weather events are the visible effects of a changing climate. We propose to develop and apply novel mathematical and statistical techniques to capture, characterize and predict extreme events. We need (1) more data on extreme meteorological events; (2) input from meteorological subject matter experts to identify particular types of extremes; and (3) new mathematical algorithms that can quantify the likelihood of particular extremes given a non-stationary background.

5. **The End of Fossil Fuels**
   Save the planet for future generations by ending the use of fossil fuels. It is time for science to speak up and push for a moon-shot program of decarbonization. We have overstepped the planetary boundaries and treated the planet without regard for the consequences. Scientists had raised the alarm long ago but failed to motivate decision makers to prepare for action.

6. **ACED: Accelerated Circular Economy Development**
   The world must more rapidly pursue the circular use of extracted minerals and manufactured products (aka "the circular economy"), and it must create new materials and innovative advanced processes from which replacement, non-petroleum-derived products can be produced. Rapid innovation — aimed at reducing waste and eliminating waste streams, reusing, repairing, remanufacturing, reprocessing, recycling, repurposing what is already available, and replacing systems, norms, products that are petroleum-reliant and/or petroleum-derived — is a necessary approach given finite global resources. Important aspects include novel lifecycle models (accounting, simulation), independently operated system optimizations, planning and investment processes linked by prices of shared inputs and outputs, research on shifting consumer behavior, strategic communications and engagement, and expedited shifts to a circular materials system, or a circular economy.

7. **Sustainable Smart Water Systems (Sustainable Water Grid)**
   We recommend investment in new research and development of a multiscale framework that transforms water management in the U.S. through more efficient resource distribution and use. Our aging water infrastructure and management practices have not kept pace with the demands of a growing population and are at significant risk due to the emerging impacts of climate change. To address these challenges within this complex system, we require technological, industrial, and social innovations that go well beyond business-as-usual. We need a nation-wide Smart Water Grid — a holistic, coordinated, multidisciplinary research framework that transforms the U.S. water infrastructure and management practices into a system that is sustainable, resilient, and will get us through the next century.

8. **Unraveling the Climate Vulnerability Web: Integration of Physical, Biological, Human Social, and Economic Models in Time and Space**
   We recommend a community-focused research effort to develop and integrate high resolution models of climate, social, ecological, and economic systems to identify vulnerabilities in human and ecological systems — and use that information to manage and reduce climate risks and increase resiliency. The effort will be carried out by teams who work in concert with community stakeholders, so decision makers and stakeholders can develop recommendations and policies to adapt to and mitigate climate change vulnerabilities in their affected communities.

9. **Change the Conversation at the Local Level**
   The discussion of climate change needs to be brought home to the local level. To achieve this goal, we propose the creation of a research program that focuses on (i) the development of a framework for evaluating novel metrics of data streams, and (ii) building community-level networks of local decision makers and leaders to evaluate how these new metrics can inform the development of appropriate incentives to improve climate mitigation behaviors. Such a program requires the combined efforts of mathematical, computational, and social, behavioral, and political scientists working collaboratively at multiple interdisciplinary centers.

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Cross-Cutting Themes

This report identifies nine areas of research to address scientific and policy issues related to climate change, sustainability, and resilience. In this section, we highlight some cross-cutting themes, including (i) a need for inter-, multi-, and trans-disciplinary collaborations; (ii) a need for a broad-based research portfolio that can provide a solid foundation for science-based decision making; (iii) a need to educate a workforce capable and willing to engage in these activities, and (iv) a need to better connect local and regional stakeholders to the research community.

Collaboration between scientists from diverse disciplines is critical for the success of all projects. For example, building a digital twin of Earth's climate system requires not only modeling and computational expertise, but also partnerships with in-silico labs to provide and integrate data from empirical sources. The traditional connections between applied mathematics and engineering need to be expanded to include practitioners in the social, biological, and physical sciences, as well as experts in computer and data science. The transition to a circular economy, the development of a smart water grid, the promotion of sustainable energy practices, and the implementation of strategies for climate change adaptation all require cooperation and team building among diverse stakeholders and scientists across a variety of fields, filling in vocabulary gaps, and broadening the databases for science-based decision making. Nontraditional modes of collaboration need to be explored.

Whether we are considering climate change, loss of biodiversity, rising ocean levels, or the increasing frequency and severity of natural disasters, the underlying cause is the same: humans are changing the environment. Our goal as mathematicians and scientists must be to better understand the dynamics of Earth's climate system, including the effects of human behavior, and to support technologies for sustainable development. The need for new mathematics is significant; examples discussed at the workshop are methods for the quantification of uncertainty, especially for nonstationary processes; early warning signals of emerging phenomena and tipping points in complex dynamical systems; attribution science, to connect the statistics of extreme events to the physics of climate change; the effect of a warming planet on the evolution of Arctic sea ice and permafrost; dealing with multiple scales (a feature of many of the big ideas highlighted in this document). Network science, artificial intelligence and machine learning are some of the new techniques that will play an increasingly important role in the process of scientific discovery.

Ideas for mitigation of the effects of climate change are urgently needed, yet must be thoroughly vetted by national, regional, and local communities affected. For example, the following require a buy-in at all societal scales: reducing energy consumption and waste; developing the circular economy and sustainable practices; sharing and development of sustainable water systems; and working towards climate change adaptation. Communities must be more fully integrated into the scientific process to have any chance that the

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proposed ideas are attainable. Suggestions included outreach activities and tools (games) to foster a better understanding of the science behind the proposed actions.

Lastly, the efforts to address the challenges associated with climate change, sustainability, and the development of clean energy must be accompanied by dramatic changes in the way the workforce of tomorrow will engage with and advance the ideas outlined above. The current educational structure is neither conducive to the creation of a well-informed community of stakeholders, nor are the scientists poised to address the many new challenges. Local and national initiatives aiming to solidify, broaden, and revise curricula of science-based education as well as engage students in hands-on projects which transcend the disciplinary silos must be complemented by fostering and developing new reward systems for educational professionals. Instructors and administrators across all levels must reinvigorate curricula to help students understand how to synthesize their learning to tackle the problems needed to ensure a healthy, life-sustaining planet.

About SIAM

The Society for Industrial and Applied Mathematics (SIAM) is an international professional society headquartered in Philadelphia, Pennsylvania with over 14,000 members from across many disciplinary areas, primarily with a shared interest in applied mathematics, computational mathematics and computing, data science, and their applications. SIAM members work in industrial and service organizations, universities, colleges, and government agencies and laboratories all over the world. Of its members in academia about one third span a wide range of disciplinary departments other than mathematics; these include computer science, the biological and physical sciences, and engineering.

The goals of SIAM are: (i) to advance the application of mathematics and computational science to engineering, industry, science, and society; (ii) to promote the research that will lead to effective new mathematical and computational methods and techniques for science, engineering, industry, and society, and (iii) to provide media for the exchange of information and ideas among mathematicians, engineers, and scientists. This is executed via six main areas of focus: publications; membership (including 22 Activity Groups, over 200 Student Chapters, and 15 geographic Sections); conferences and meetings (about 20 annually); programs and resources; advocacy; and partnerships.

SIAM publishes 18 peer-reviewed research journals and an online undergraduate research publication, and over a dozen textbooks and monographs each year that are the leading source of knowledge for the world's applied mathematics and computational science communities. The Society also publishes *SIAM News* ten times per year (digitally and in print), which reports on novel applications of mathematics and new uses of mathematical methods in areas from medicine to climate modeling.

SIAM Activity Groups provide an intellectual forum for SIAM members interested in exploring a particular area of applied mathematics, computational science, or cross-

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disciplinary application. There are a few activity groups that immediately come to mind when considering *climate science, sustainability, and clean energy*.

The SIAM Activity Group on *Mathematics of Planet Earth* describes itself as follows: “We are for mathematical and computational scientists who care about the future of our planet. We are a multidisciplinary activity group studying Earth's climate system and the effects of climate change; issues of resilience, sustainability, and biodiversity; and the impact of human activities on the environment.”

Current and past chairs of the Mathematics of the Planet Earth SIAM Activity Group at the Convening: Katherine Evans, Hans Engler, Lea Jenkins, and Hans Kaper.

Secondly, the SIAM Activity Group on *Geosciences* is where “modelers concerned with problems of the geosciences can share their problems with algorithm developers, applied mathematicians, numerical analysts, and other scientists. Topics of interest include flow in porous media, multiphase flows, phase separation, wave propagation, combustion, channel flows, global and regional climate modeling, reactive flows, sedimentation and diagenesis, and rock fracturing.”

The *Uncertainty Quantification* activity group fosters activity and collaboration on all aspects of the effects of uncertainty and error on mathematical descriptions of real phenomena, error and uncertainty in analysis and predictions of the behavior of complex systems, including biological, chemical, engineering, economics, financial, geophysical, physical, and social/political systems. The 2022 SIAM Conference in Uncertainty Quantification features several research talks relating to climate modeling. Many of those presentations represent collaborative work with multidisciplinary teams consisting of researchers from national labs, academia, and federal agencies. The *Life Sciences, Mathematical Aspects of Materials Science, Data Science*, and *Dynamical Systems* activity groups have members who do important research relevant to our areas of concern, as well.

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Convening Recommendations

This section gives details on the nine recommendations that emerged from the convening. The figure below illustrates how the recommendations fit the Convening's six main goal areas.

	Accelerate Clean Energy Innovations	Advance Scientific Knowledge	Anticipate Future Conditions	Increase Climate Change Resilience	Outreach & Broader Impacts	Promote Sustainable Practices
1 Digital Twins	X	X	X	X	X	X
2 What Happens in the Arctic Does Not Stay in the Arctic		X	X	X	X	
3 Transforming Education to Address Complex Futures	X	X	X	X	X	X
4 Extreme Learning		X	X	X		
5 The End of Fossil Fuels	X			X		X
6 ACED: Accelerated Circular Economy Development						X
7 Sustainable Smart Water Systems (Sustainable Water Grid)		X	X	X	X	X
8 Unraveling the Climate Vulnerability Web: Integration of Physical, Biological, Human Social, and Economic Models in Time and Space		X	X	X	X	X
9 Change the conversation at the local level	X	X	X	X		X

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1. A Paradigm for Digital Twins to Safeguard the Planet

What is your Big Idea?

To develop a multi-fidelity, scalable, long-lived open-source platform to build problem-specific digital twins designed to:

- Continuously adapt as new data is ingested
- Detect changes in the climate system
- Measure response to climate mitigation actions
- Integrate scientific understanding through in silico simulations
- Inform policy decisions
- De-risk by being uncertainty-aware.

What Goal Area(s) does this address?

- Develop a community of practice around the Digital Twin paradigm, which consists of protocols that enable systematic analysis of Earth system processes, including quantification & analysis of dynamic uncertainty.
- The core goal areas addressed:
    - Advance Scientific Knowledge of Earth system dynamics at multiple scales
    - Anticipate future conditions
- With problem-specific uncertainty-aware Digital Twins built to:
    - Increase climate change resiliency
    - Accelerate Clean Energy Infrastructure transitions
    - Increase outreach and broader impacts
    - Promote sustainable practices through better informed decision-making
- The critical infrastructure developed will enable better decision-making in the face of deep uncertainty
- Develop systematic modeling and analysis protocols to accelerate innovation, learning, and stakeholder engagement through
    - Simulation-based inference (variational Bayesian inference)
    - Causal Modeling & Inference
    - Stochastic and Differential Programming
    - Systematic analysis of dynamic uncertainty.

What is required to pursue this?

An interdisciplinary collaboration between:

- Math modelers
- Scientific domain experts (for the problem-specific digital twins)
- Software engineers (including programmers)
- Social scientists.

Usage of contemporary open science practices such as:

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- Adoption of FAIR (Findable, Accessible, Interoperable, and Reusable) guiding data principles
- Adoption of standards (where relevant) by working with organizations including the Open Geospatial Consortium (OGC) and the Earth Science Information Partners (ESIP).

Additional resources:

- Access to massive computational infrastructure (compute and storage)
- Long-term (~100 y), sustained investment & software maintenance.

Expected Value and Impact:

- The Digital Twins continuously adapt as new data is ingested to make the state AND dynamics consistent with observations (and each other)
- Mathematical and statistical methods are abstracted to enable continuous adaptation for problem-specific dynamical systems
- Detect "change/tipping points" including responses to climate mitigation measures (e.g., from carbon capture and storage and nature-based solutions)
- Make policy decisions to start or optimize climate mitigating measures along with confidence levels.

What are the broader impacts of this idea?

- Inter/multi/cross-disciplinary long-term effort spanning many different disciplines: math, engineering, computer science, geosciences, economics, political science, psychology, sociology, etc.
- Potential of generating huge amounts of data for education and experimentation purposes
- Prototype model for global cooperation between the U.S. and other countries
- Training of the next generation workforce.

What is the reasoning, justification, and/or supporting evidence behind the idea?

Other open-source and "Digital Twin" initiatives are underway (e.g., NSF's Earth Cube, DOE's E3SM, and Singapore's Nationwide Digital Twin). The European Union recently launched development called Destination Earth:

> "An interactive system where you can change things in a digital world, which in turn helps you plan, define and operate assets such as dikes, wind farms, or flood dams". (Peter Bauer, ECMWF)

By using the latest developments in mathematics, statistics and computing, the U.S. can supersede existing efforts by providing a systematic approach to continuous-adaptation and uncertainty quantification. Combating climate change calls for an integrated, long-lived, and uncertainty-aware approach capable of:

- Handling multiple, heterogeneous, and noisy time-lapse data sources to make inferences on the state of the system by drawing samples from learned neural net surrogates for the posterior distribution of the system's state
- Using *in silico* simulations to train its neural networks to make predictions (e.g. via Bayesian Inference) of the state of the evolving system conditioned by the collected data and understanding system's dynamics
- Development of sophisticated math-inspired abstractions to facilitate FAIR principles for data and modeling
- Training its networks according to multiple modeling scenarios
- Determine which type of dynamics best explains the most current observed data (e.g. via Bayesian Model Inference)
- Systematic uncertainty quantification with learned-surrogates
- Simulate future scenarios on samples of the state to predict the impact of climate mitigation measures
- Compared to traditional simulation initiatives, uncertainty-aware Digital Twins invert observed time-lapse data for the system's state using established techniques from simulation-based inference.
- Because Digital Twins update themselves as new data comes in, they are always current and therefore capable of drawing samples of its current state that can be used to make predictions of future states according to different scenarios.
- Uncertainty-aware simulation-based Digital Twins differ from existing approaches by enabling systematic analysis of Earth system processes and include analysis of dynamic uncertainty.

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2. What Happens in the Arctic Does *Not* Stay in the Arctic

What is your Big Idea?

From micro to macro in the Arctic climate system.
The Arctic is ground zero for climate change. It is warming rapidly and giving us a warning – the planet is sick. Melting sea ice, thawing permafrost that releases methane, and threatened ecosystems are symptoms of the illness that affects society, the economy and our way of life as we know it, both regionally and globally. However, what happens in the Arctic doesn't stay there. Like a rock thrown in a pond, the adjacent land masses of the Northern Hemisphere, as part of our interconnected multiscale climate system, feel most acutely the "waves" from the big splash just to the north. Ripple effects from the massive changes in the Arctic region can alter precipitation patterns vital to the corn fields in the midwest, divert storm tracks critical to the ski industry in the west, and help bring about the hot dry conditions that lead to devastating wildfires. Understanding the symptoms, like the loss of sea ice and thawing of permafrost, at the micro level and building up from there is analogous to giving the patient hope with a powerful new diagnostic tool. It will help us make better models and predictions of what's happening at ground zero, and enable us to better understand and respond to the cascading effects we experience in the United States.

Successful application of multiscale modeling from the micro to the macro, melded with novel experiments and existing data sets, has occurred in many other areas such as statistical mechanics and materials science, but has not been developed to solve the all-important problems of creating across-the-scale models for the Arctic.

Sea ice behavior is far from well understood. The growth, break-up, and dynamics of the ice cover involve such processes as ridging, lead formation, fracture, floe aggregation, melt pond evolution, and the impact of waves on the marginal ice zone, a transitional region between the open ocean and dense pack ice. The material properties of the ice determine the myriad ways in which these effects lead to ice pack breakdown and melting in a warming climate. These ice-as-material properties are formed at the microscale level where the ice exhibits intricate heterogeneous structures that result from varying temperature, salinity, ocean interaction and even the biology of organisms present in the ice and ambient waters, including robust algal stocks that play a critical role in the global carbon cycle. The high degree of local heterogeneity in the sea ice system on many scales induces uncertainty in knowing its properties and resulting behavior, which must be inherently accounted for in developing a new modeling framework which starts at the bottom.

Sea ice is a multiscale composite, from the millimeter-scale brine inclusions and centimeter-scale polycrystalline microstructure which control mechanical, thermal, electromagnetic and fluid transport properties, to the ice pack itself, which can be viewed as a granular composite of ice floes, meters to tens of kilometers in extent, in a seawater host. Modeling of large-scale sea ice behavior has been dominated for decades by coarse-grained numerical models based on a top-down mechanistic framework developed half a century ago. While

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they have proven extremely useful for long-range projections and exploring future scenarios, they are not readily adaptable to account for the effects, for example, that lead to ice break-up, and they are not built to capture the many critical sub-grid and meso-scale processes where fine-scale structure is essential to the behavior.

The closely related **permafrost** system raises completely analogous questions. The permafrost models of today are best suited to the geotechnical scale of meters, but they are being asked to account for a slew of complex coupled processes for which they are not designed. The inclusion of these processes is needed to answer questions about the local and global response of the active layer of permafrost to warming temperatures, including local infrastructure failure and coastal decline, as well as the resulting dynamics of the biosphere and climate system through the release of stores of highly potent greenhouse gasses. Current models are reasonably well suited to local predictions since they can emphasize either the fluid or mechanical aspects, as relevant to the local environment.

Predictions at the larger scale, however, need incorporation of all phases and processes, which are in turn determined by smaller scale processes. Additionally, quantitative predictions need the incorporation of data, but these are sparse and inconsistent, with empirical data in cold regions being particularly challenging to obtain, and with strong local heterogeneities. The first-principles based understanding of the microscale processes and the improved up-link between microscale and mesoscale would form the foundation of *in-silico* labs and tools to provide the predictions of large-scale processes. The development of a multiscale paradigm of complex transient processes with injection of new data is the main modeling challenge of our age if we are to get a real picture of the fate of permafrost, the gasses underneath, and the potentially massive impact on the biosphere and climate of greenhouse gasses being released.

Overall, the way the small-scale effects add up to control the larger scale mechanisms is not understood at the physical level for models in the Arctic. Nevertheless, multiscale hierarchical modeling offers us an approach through the development of complex cross-scale models to transfer the critical information from these microscales to the macro behavior. This upscaling can be physics-informed and data-driven where possible but may rest on mathematical constructs where the physics is not yet determined and when experiments are not available.

What Goal Area(s) does this address?

- Advance scientific knowledge - in particular, advance the science of climate change and two of the most critically important components of the climate system, namely, the polar sea ice covers and permafrost; advance applied mathematics, theoretical physics and computational science through the grand challenge of creating a new modeling framework for complex multiscale components of the climate system

- Anticipate future conditions - improve projections and models of sea ice and permafrost behavior to better explore future scenarios as well as the impact on the U.S. of changes in the Arctic

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- Increase climate change resilience through better understanding of the basic dynamics of sea ice and permafrost in a warming climate, and better models of how to respond and mitigate the effects downstream

- Increase outreach and broader impacts for mathematics, climate science and highly interdisciplinary research; the combination of multiscale mathematical modeling and computation with Arctic field experiments and many types of projects in between provide myriad opportunities for students, as well as for outreach to the broader public.

What is required to pursue this?

We recommend that a community be built, with sufficient critical mass and contributions from many disciplines to overcome historical inertia, to develop a new paradigm for sea ice and permafrost modeling, with the goal to incorporate multiscale and complex components of the climate system. We must use vast amounts of historical and new dynamically changing data from sources including remote sensing platforms, and methods from various disciplines and powerful computational tools to derive macroscopic behavior from microscopic laws and information. Moreover, it would be essential to conduct lab and field experiments specifically designed over a broad range of scales to dovetail with the modeling efforts.

This community would consist of various types of interdisciplinary teams of researchers, engineers, and stakeholders, depending on the type of project, its scale, the relative levels of theory, computation and experiment, and a center coordinating the various types of theoretical, computational, and experimental efforts. There would be three basic (related) categories for types of projects: sea ice, permafrost, downstream impacts in the U.S. of Arctic change.

The teams of researchers, engineers, and stakeholders would be built from appropriate combinations of the following: mathematical and computational scientists, data scientists, software engineers, geophysicists, physicists, materials scientists, experimentalists, atmospheric and climate scientists, physical and biological oceanographers, electrical, mechanical and civil engineers, remote sensing scientists, local stakeholders in Arctic regions, industrial partners and stakeholders in the U.S. such as representatives from policy making bodies, and the agricultural, energy and snow sports industries, to mention a few.

There are many research questions to address. How do we create hierarchical models where computations and models of effective behavior are passed up the chain of scales, in view of the stochastic character of the data, as well as data gaps? What types of small-scale laboratory and larger-scale field experiments must we design to inform the modeling efforts? There is need to establish new frameworks and new methodologies, from the “ground up” rather than the “top down” to rigorously, efficiently and accurately model key processes and larger scale dynamics – that would revolutionize our understanding of critical processes that have a big impact on the climate system, our ability to make projections of the future trajectory of the Arctic and its ecosystems, and provide a novel basis for studying the impacts of Arctic climate change on the rest of the world.

This research thrust requires:

- Funding on the scale of $10M per year for 10 years (2-3 cycles of 3–5-year awards) for smaller and larger interdisciplinary and multi-institutional teams for pilot/exploratory investigations as well as full research projects.
- Establishing a $10M center/institute to coordinate research efforts from theory to experiment, and support a large-scale distributed research infrastructure of cryo labs, imaging and computational support, and field work to engage the best expertise from across the U.S. and abroad. The center would also have responsibility for coordinating and promoting the exciting broader impacts possible here, set up workshops, and coordinate data collection and stewardship. In all projects, involvement of industry, stakeholders, and other research labs, as well as leveraging other funding is encouraged; the possibility of international collaborations should be exploited.
- In addition, the projects would need $10M for 2 dedicated expeditions to the Arctic region over the course of the 10 years to inform and validate models, and to "piggy-back" opportunistically on many other expeditions around the world.

Expected Value and Impact:

Fundamentally new mathematical ideas on multiscale methodologies and computational tools, plus data collection, storage, and imaging technologies suited to multiscale analysis will be developed for complex Arctic systems. These are needed since the Arctic is perhaps the least understood critical component of Earth's climate system. Simultaneously, in view of the tremendous long term and broad impact of similar approaches in materials science, solid state physics, porous media, and statistical mechanics, this new paradigm will have great potential to be transferred to other fields. They include, for example, polar ecology which also has a multiscale structure, from sea ice microbes living in the brine inclusions whose sizes span many orders of magnitude, to polar bears moving through a multiscale ice/ocean composite environment. The spatial organization of these organisms has hierarchical characteristics, as imposed by the multiscale structure of the sea ice system. Our modeling advances would also likely be integrated into a new generation of global climate models, as well as provide new directions and approaches for advancing models of the entire hierarchical climate system.

The center will connect the broader public to the goals of climate research and specific deliverables, as well as to exciting interdisciplinary research and field experiments in one of the most extreme environments on Earth. They will be able to experience and learn about climate change where it is happening the fastest, and explore the fundamental role that mathematics, theory, and computation play in modeling Earth's climate system, and in understanding the significant ripple effects from the dramatic changes in the Arctic.

The center and research projects will be part of the action to mitigate and effectively respond to sea ice loss and permafrost thawing. The ability to improve projections of the cascading effects of sea ice loss and permafrost thaw on the precipitation patterns, release of greenhouse gasses, and freshwater availability and more broadly weather and climate

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patterns in the U.S., will affect socioeconomics, geopolitics, energy policy, national security, food security, etc. Furthermore, the research outcomes and broader impacts will be appreciated by the Arctic and non-Arctic based stakeholders.

What are the broader impacts of this idea?

The center and projects will educate new generations of scientists on the basics of interdisciplinary math and science and develop their ability to build and use advanced models, and to break from, yet also learn from, older paradigms. It is crucial to involve high school, undergraduate and graduate students and postdoctoral scholars by way of fellowships, expeditions, internships, and research opportunities related to Arctic research. Projects should be made as attractive as possible to draw in as many as possible to climate and math research, with particular attention to engaging members of underrepresented groups; substantial outreach activities will be carried out to engage stakeholders in Arctic regions as well as sub-Arctic and non-Arctic regions.

What is the reasoning, justification, and/or supporting evidence behind the idea?

Warming in the Arctic has led to rapid, precipitous declines in sea ice and to thawing of the permafrost, both of which can lead in turn to further warming on a global scale. These dramatic changes in the Arctic environment impact not only the climate, ecology, economics, infrastructure, transportation and human activities in the region, but also have significant, cascading effects on the rest of the world and the U.S. in particular. Yet, our understanding of the large-scale dynamics of these processes is far from accurate or comprehensive because it is primarily based on top down models which lack precision from their fundamentally coarse-grained nature.

Significant advances are needed to rigorously compute effective material properties of sea ice and permafrost from information about the composite microstructure and microscale processes, and build up hierarchically from there. The tremendous success of mathematical theories and computational frameworks, statistical mechanics, and rigorous homogenization methods in the theory of composite materials have helped trigger the widespread use of composites throughout today's technological world. **It is time to bring these advances to Arctic research.**

WHY NOW? The ice is melting and the permafrost active layer depth is moving down with the danger of releasing greenhouse gas! Also, the largest Arctic expedition in history gathering tremendous amounts of data on climate change in the polar marine environment, MOSAiC, finished recently. The time is right to develop the next generation of sea ice and permafrost modeling which thoroughly leverages these vast, modern data sets. Simultaneously, Arctic permafrost data need to be analyzed and the models augmented and improved, with the knowledge gaps identified before irreversible changes happen in this environment, with global implications.

WHY NSF? Fundamentally new ideas, theories and techniques are needed to advance to a paradigm based on multiscale modeling of complex coupled processes involved in sea ice and permafrost dynamics. Such developments in mathematics and beyond require theoretical breakthroughs as well as new ways of building interdisciplinary connections,

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using and acquiring data, and closing the loop between theory with real world data, taken in experiments developed to dovetail with the multiscale hierarchical nature of the models. NSF has the needed scale, the interdisciplinary culture, the resources and stature to facilitate leveraging additional support for all aspects of the recommendation – to facilitate the success of the first sustained effort to establish a new multiscale paradigm, from micro to macro, for modeling sea ice, permafrost and complex Arctic systems.

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3. Transforming Education to Address Complex Futures

What is your Big Idea?

The world is facing challenges of increasing complexity, and the pace of change is accelerating. A complex future has elements of risk, ambiguity, volatility, uncertainty, high impact to life/health/environment/security/economics, and extreme conditions for which there are no immediate analogues to reference. Math, modeling, data science, and systems analysis are central to research and solutions for complex problems, but students today often find it difficult to place coursework into a broader context and to bridge subject areas. Additionally, studies have shown that classroom-acquired knowledge becomes obsolete at increasingly shorter intervals, making it imperative that students acquire skills and tools that enable them to move beyond classroom context.

To address the need for a nimble and collaborative workforce (in industry and research) prepared to address today's complex problems, education has to be transformed to teach students systems, values, and visionary thinking. The approach should permeate the entire educational college experience, from general education through capstone projects. This does not imply that all existing curricula have to be discarded. However, transdisciplinary thinking and broader context should ideally play a role in all coursework. Thus, *a collaborative approach to curricula, classes, and pedagogy should be developed that crosses boundaries among STEM, social science and other disciplines to graduate* ***thinkers*** *who can contribute professionally and personally to solutions for society's Grand Challenges (e.g., climate, human health, food security, national security).*

What Goal Area(s) does this address?

This concept contributed most directly to the goal area to "Increase Outreach and Broaden Impacts". However, by preparing a workforce to tackle grand challenges in a complex future, the effort is also critical to achieve progress in the other goal areas to

- Anticipate future outcomes
- Advance scientific knowledge
- Accelerate clean energy innovation
- Increase climate change resilience
- Promote sustainable practices.

What is required to pursue this?

Implementation of this idea requires a shift toward a collaborative, less siloed mindset within academia and between academia, industry, and government. Three steps are envisioned to get there:

- A (3-5 year) pilot period, when multiple institutions develop and test transformative strategies for curriculum design and pedagogy.
- An assessment period, where successful strategies are identified and refined.

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- A broad promulgation of lessons learned through replication and continued innovation. At all stages, stakeholders – including students, faculty, university leadership, industry, non-profit organizations, and government – should be consulted to ensure that disparate needs and ideas are being addressed. The projected timeline through broad-scale adoption is anticipated to be around 10 years. Funding opportunities can be structured along lines similar to NSF's ADVANCE program.

Curricular and course adaptation for undergraduates should happen at multiple levels:

- Grand challenge themes should be incorporated as a common thread in general education courses, so that students will experience a more cohesive curriculum. Multiple such themes could be offered, so that students can focus on what motivates and interests them.
- The content and pedagogy in existing disciplinary-specific courses should be revised to be more responsive to today's needs and taking advantage of today's technology.
- All students should be involved in a multi-disciplinary capstone project, individual research, or internship that exposes them to the interplay between math, natural sciences, social sciences, engineering, and/or communications and the arts. Ideally, these projects would address a complex real-world problem.
- Teacher-training for the K-12 population will benefit additionally from these reforms, by teaching future teachers to bring systems thinking into their classrooms.

These changes need to be supported by robust faculty training, to shift the focus from teaching students to replicate to educating students to think, draw connections, and expand upon classroom knowledge. This can initially be based on existing, published strategies, but should continually be adapted to incorporate new successes.

Such transformational revamping of undergraduate education requires significant commitment from academic institutions. In particular, institutions will need to:

- Change academic structures to encourage and reward collaboration across departments and reduce department-scale bean counting by adopting such practices as recognition in tenure and promotion guidelines of interdisciplinary efforts, cross-listing of coursework, and valuation of work on applied projects and community service.
- Establish and revise interdisciplinary degree programs and curricula.
- Incorporate industry/government/non-profit partnerships to aid in the development and assessment of job-market relevant degree programs and to provide research problems for capstone projects.

Assessment needs to be fully integrated into the pilot programs, preferably through collaboration with education experts and incorporating feedback across stakeholder groups. For the broadest impact, piloting institutions should partner with other institutions, including continuing education programs and community colleges, to build cross-institutional relationships.

Expected Value and Impact:

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The adoption of revised educational paradigms can meet the needs of both students and industry through university-wide transformation of curricula that better prepares students for complex futures. Integrating industrial partners more closely into the education pipeline will:

- Offer new insights into the pedagogical process
- Attract new students into STEM associated fields and improve retention rates
- Enhance workforce readiness and align degree programs more closely with emerging societal needs.

The approach outlined in this document will result in such innovations as:

- Pedagogical practices that promote more active and engaged learning through incorporation of relevant issues and context into lessons
- Adoption of curricula that are adaptable to university strengths while promoting interdisciplinary work
- Replicable framework to expand successes to additional campuses following the pilot and for consideration by accreditation bodies
- Education research results that define components that lead to the greatest positive impacts
- Disruption of academic silos and traditional academic reward systems to improve inter/transdisciplinary education and/or research collaboration teams.

The intent of these impacts is not to displace existing university programs and strengths but to leverage complex systems thinking to supplement in-depth disciplinary studies with understanding of the broader context.

What are the broader impacts of this idea?

The proposed educational transformation will lead to college graduates that are better prepared to collaborate with colleagues from other backgrounds to tackle today's complex challenges. We anticipate wide-reaching benefits, such as:

- Improved U.S. leadership and economic competitiveness through greater capacity for innovation
- General increase in public awareness of issues surrounding complex problems, for example sustainability and climate
- Improved general numeracy as K-12 and community learning are implemented.

What is the reasoning, justification, and/or supporting evidence behind the idea?

Work to prepare for complex futures is timely, given the recent, global examples of extreme weather, clean energy and its role in energy security, the global pandemic, and supply chain challenges. However, our current education structure is not set up to contribute to the truly interdisciplinary and transdisciplinary approaches necessary to address these challenges.
Academic silos still dominate educational institutional degree programs and professional preparation, even though faculty increasingly identify with more than one field. We need more work to ensure that (eventually) students in all majors have an increased awareness of these problems through interdisciplinary courses and project work so they understand

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their role as a citizen and professional, and have the capacity and skills to develop and contribute to solutions.

The National Science Foundation "...supports basic research and people to create knowledge that transforms the future". NSF has a unique position at the interface of scientific advancement and education, with expertise across disciplines and focus on far-reaching efforts that advance society. NSF also has experience with funding award structures that could be applicable to this topic, making implementation more straightforward.

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4. Extreme Learning

What is your Big Idea?

A challenge to develop and apply novel math to capture, characterize and predict extreme events in a changing climate

What Goal Area(s) does this address?

- Anticipate Future Conditions
- Increase Climate Change Resilience
- Advance Scientific Knowledge.

What is required to pursue this?

Our proposed research has three main requirements: more data for extreme weather events; stakeholder input on the types of extremes to focus on; and new mathematical algorithms that can forecast extremes (or tail events) given a non-stationary background.

Data collection will overcome a key challenge in predicting extremes: extremes, by their very nature, are rare, so limited data exists to characterize extremes and their driving processes. Our research program will determine data sources and needs for future data collection efforts and assess the quality of existing data.

We also require stakeholder meetings, including with infrastructure planners and operators, to identify initial types of extremes for our focus. These meetings will prioritize diverse stakeholder representation to maximize value of research in improving equitable outcomes.

Finally, this research requires fundamental advances in mathematics and statistics that allow us to accurately predict extremes - not averages - under a non-stationary background.

Computing and data storage needs will be significant for the project.

Initial phases of research will require transdisciplinary collaborations between climate scientists, meteorologists, mathematicians, statisticians, and computer scientists. Later phases of research will integrate our improved understanding of extremes with users of extreme weather forecasts, including engineers and social scientists.

Sensors development and deployment can support the development and validation of both physics-based and data-driven models and their combination. Optimal experiment design can support decision-making and the efficient collection of new data, by identifying areas of higher uncertainty.

The modeling framework and mathematical tools will need to be supported by the creation of new infrastructure, policies and methods for verification, validation, and assurance.

Expected Value and Impact:

This effort will contribute substantially to anticipating future conditions for the climate system. In particular, tools and approaches will be developed to map out climate scenarios in much greater detail, focusing on rare but powerful events that have the largest impact on human wellbeing and on ecosystems. It will also become easier to identify and describe regional effects of extremes. Possible scenarios will be explored in more realistic ways, going beyond the current practice of using global trends to parametrize the scenario space. This will be done by incorporating physical modeling systematically to account for nonlinear feedback effects and by incorporating regional tipping point phenomena with uncertain timing.

The new mathematical and computational framework needs to incorporate existing data on extreme events, and it will be used to create scenarios for the probability distribution of future extremes. The prediction includes the frequency and expected magnitude of the events. A significant leap is required in the spatial and temporal resolution of the models and the predicted scenarios. Interpretability and explainability are essential features of the models, to use them as a support to decision making and action.

Prioritizing actions in decision-making and intervention at multiple scales relies on accurate predictions of alternative scenarios, and on being able to anticipate catastrophic events and possible cascade effects. The result of mitigating measures can also be simulated, to predict the most efficient use of resources and unforeseen effects that result from action or inaction. Local and global government and agencies, private and public entities, communities, and individuals need a scientific and quantitative basis for short and long-term decisions.

Our scientific understanding of the climate system and of the impact of climate change will be advanced at all levels. New frameworks for describing and understanding probability distributions for extreme events will be created to deal with the specific challenges of spatial correlation, nonstationarity of underlying background processes, and systems that move into less well understood regions of their state space. This will be done by leveraging new machine learning methods, developing novel statistical techniques, and integrating physical models and regional causes for nonstationarity such as tipping points. At the same time, new ways to extract, condense, and ultimately communicate essential results will be developed, contributing to broad advances in data science. We expect the new scientific knowledge and modeling framework will have broad applicability to understand and forecast rare events in a wide range of problems beyond climate science (e.g., fracture, cascade failure, etc.).

Most climate extremes are disastrous for the affected humans and natural world. Climate change is broadly expected to make such disasters more frequent or even more severe, and new compound events are unfortunately more and more likely to happen. The expected outcome of this effort in the medium term will be to make it easier to prepare for such events and to mitigate their impact. It will increase climate change resilience especially for poor and underprivileged communities and developing countries.

What are the broader impacts of this idea?

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- Inter/multi/cross-disciplinary long-term effort spanning many different disciplines: math, engineering, computer science, geosciences, economics, political science, psychology, sociology, etc.
- Potential of generating huge amounts of data for education and experimentation purposes
- Prototype model for global cooperation between the U.S. and other countries
- Training of the next generation workforce.

What is the reasoning, justification, and/or supporting evidence behind the idea?

NSF is uniquely positioned to undertake this broad interdisciplinary basic science challenge with immediate and urgent impact. There are significant science questions to build new Artificial Intelligence (AI)/Machine Learning techniques together with new statistical techniques that capture and predict extreme climate events, to verify them against earth- and satellite-based observations, as well as to translate extreme climate predictions to local climate impact such as storm damage, flooding and, heat outcomes. These challenges require significant advances at the frontiers of their respective fields. The program is a natural extension of the foundation that NSF has already laid through one of its Expeditions in Computing and more recently with its AI Institute on Weather, Climate and Oceanography (AI2ES). Establishing U.S. leadership in this new area is critical to national prosperity, as resilience to climate events is arguably among the most important challenges of the 21st century. Integration of the new knowledge created by this program into the education and training of next generation scientists is best addressed by NSF funded work.

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5. The End of Fossil Fuels

What is your Big Idea?

Save the planet for future generations by ending the use of fossil fuels. We need strong support for the basic research needed to accelerate a national effort to eliminate the need for fossil fuels — a moon-shot program of decarbonization.

This project is consistent with the U.S. goal of achieving net-zero GHG emissions by 2050; see:

- The White House report, The Long-Term Strategy of the United States: Pathways to Net-Zero Greenhouse Gas Emissions by 2050.
- The U.S. Department of Energy's Industrial Decarbonization Roadmap

What Goal Area(s) does this address?

- Accelerate clean energy innovations
- Increase climate change resilience
- Promote sustainable practices.

What is required to pursue this?

This is an ambitious goal that requires progress on many levels. Needed in particular are:

- The formation of multidisciplinary teams that bring together scientists, engineers, social scientists, and industry. As the project has many different levels and distinct challenges, many teams are needed to address them.
- Coordinated support from multiple funding agencies and, within NSF, multiple divisions.
- Timeline:
  - 5 years to start up, identify topics, recruit team members, and begin implementation
  - 10 years until first significant results provide accelerated progress towards a net-zero carbon economy
  - 25 years to complete implementation of a net-zero vision.

Expected Value and Impact:

- Reduce energy consumption
- Increase energy efficiency
- Electrify what can be electrified
- Develop renewables for what cannot be electrified
  - Biofuels, hydrogen, methanol, etc.
- Manage the transition to a fossil-free state.

Note that from methanol and some biofuels, other fuels such as kerosine (for jet fuel) or diesel (for ships or long-distance trucking) can be obtained in a carbon-neutral fashion, i.e.,

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when burning these fuels, only as much CO2 will be released as was extracted before from the atmosphere. Also note that this enables the production of plastics without having to use fossil fuels.

What are the broader impacts of this idea?

Broader impacts are numerous and diverse. Examples are:

- Dramatic reduction of carbon emissions
- Significant improvements in quality of life, health, and environment
- Creation of green jobs
- Independence from oil and gas
- Increased geopolitical stability
- Localized energy production ("power to the people")
- Reduced transportation costs
- Local jobs, local resilience.

What is the reasoning, justification, and/or supporting evidence behind the idea?

We have overstepped the planetary boundaries and treated the planet without regard for the consequences. Scientists had raised the alarm long ago but failed to motivate decision makers to prepare for action. It is time for science to speak up and push for a moon-shot program of decarbonization.

NSF has the intellectual standing to propose a science-based approach to decarbonization and can do its part by supporting the basic research needed to accelerate a national effort to eliminate the need for fossil fuels.

Mathematical modeling, data analytics, network science, machine learning, and high-performance computing all play a fundamental role in this work.

Recent advances in data assimilation — techniques to integrate multimodal data streams from satellites, in-situ observations, and large-scale numerical simulations into climate models — have resulted in significant improvements in weather and climate prediction; see, for example, [Geophysical Research Letters, Schneider et al, 2017]. Similarly, new analytical and computational techniques need to be developed, for example to improve the efficiency of green energy production processes, to improve the energy storage capabilities of batteries and fuel cells, to discover new materials that enable energy production and conversion processes, to incorporate large numbers of renewable energy generators into the power grid, to design green buildings that consume less energy, etc.

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6. ACED: Accelerated Circular Economy Development

What is your Big Idea?

The fossil fuel, or petroleum, industry and its ability to rapidly and effectively adapt to changing consumer norms is the "elephant in the room" that must be addressed head-on in order for society to have any hope of achieving its climate change and sustainability goals. It is not sufficient to simply say "down with fossil fuels" without directly tackling the ubiquitous impacts of petroleum reliance in very tangible ways. Countless products upon which consumers, worldwide, depend for daily livelihood are derived from petroleum processes: food packaging in the form of plastics, medical supplies and devices, pharmaceuticals, transportation fuels, fertilizer for crops, components for manufactured items both large and small, and the like. The list is seemingly endless. Commensurate with this is the situation that the global population has largely become a "throw away" society." As a result, the world is facing a system-wide crisis of unmitigated leakage of petroleum into all aspects of human life, unmanageable waste, and overuse of natural resources that is clearly exacerbating the frequency and immensity of natural disasters already being encountered across the globe.

The need to address these issues is urgent and critical, requiring a fast-tracked, two-pronged response in order to reverse the status quo. The world must more rapidly pursue the circular use of extracted minerals and manufactured products (aka "the circular economy"), and it must create new materials and innovative advanced processes from which replacement, non-petroleum-derived products can be produced. These are both massive tasks that address massive-scale problems which are confounded by the need to tackle them in a way that promotes consumer acceptability (cost-consciousness and fit-for-use), equity, and global economic stability. Together, they represent a comprehensive approach to achieve a truly circular economy that minimizes, and ultimately eliminates, the reliance on petroleum and its derivatives. The approach is operationalized through rapid innovation aimed at reducing waste and eliminating waste streams, reusing, repairing, remanufacturing, reprocessing, recycling, repurposing what is already available, and replacing systems, norms, products that are petroleum-reliant and/or petroleum-derived.

Fast-tracking this initiative requires integration and strong cross-disciplinary collaboration of individuals and groups across the STEM disciplines, closely integrated with the social, economic, and behavioral sciences, direct inclusion of various stakeholders, including nonprofits, NGOs, and multiple communication and media venues, and a re-education initiative across all levels aimed at literally changing the way people navigate their daily lives. Important aspects include novel lifecycle models (accounting, simulation), independently operated system optimizations, planning and investment processes linked by prices of shared inputs and outputs, and expedited shifts to a circular materials system, or a circular economy.

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Pricing or true valuation of waste provides incentives for innovation that coupled to policy and behavior modifications will generate beneficial changes in investments at the margin. Without a doubt, considerable work is already underway in this arena. However, to use a simple analogy, the current state is, "the bathtub is filling up faster than we can drain it." The rate at which these initiatives are progressing and the extent of their collective impacts is not enough to overcome the rate at which waste is accumulating and petroleum is infiltrating daily life. Hence, we propose a moonshot type of initiative to integrate, expand, and rapidly accelerate the various programs already in play.

The 2020 report "NSF Convergence Accelerator: Design for Circular Economy from Molecules to the Built Environment Workshop Report" largely represents the style and extent of the initiative that we propose. It defines and contrasts the circular economy in the following way: "In contrast to linear models, circular economy (CE) aims to decouple economic growth from resource consumption by cycling products and materials back into production, either by returning materials to generate new products, or by releasing benign substances to the environment through degradation. Leakage from the system will be correctly priced. CE principles are based on the efficient use of resources and eliminating waste from product life cycles; a truly circular economy keeps material in continuous use by design." Still, we believe an even further expansion and more rapid implementation of the recommendations in this report to encompass the parallel concomitant petroleum replacement aspect is required in order to truly make an impact at a timescale that will make a difference. The situation is critical and there is no time to lose!

What Goal Area(s) does this address?

A multifaceted acceleration of circular economy principles addresses key goal areas associated with sustainability and climate change. These include:

- Waste reduction through accurate pricing, stimulating investment in new approaches
- Rapid decrease of carbon-based/driven problems
- Enhanced facilitation of alternatives to fossil fuels and petroleum derivatives and/or reducing economic dependency on fossil fuels
- Necessary conservation of the finite reservoir of earth's materials and precious resources, actionable, achievable, scalable, and pragmatic progress towards desired climate goals, equitable sustainability, and
- Increased inclusion of, and collaboration among, all potential stakeholders including the petroleum companies and professionals as well.

What is required to pursue this?

To embark on a comprehensive, rapid-paced conversion to a circular economy, a cross-disciplinary approach is needed and full engagement with policy makers is a prerequisite. This will require expertise from a variety of disciplines, including the quantitative sciences (computing, data, statistics, and mathematical modeling), various aspects of engineering (systems, industrial, mechanical, control), physical and life sciences, economics, behavioral/social sciences, communications, education, industry and manufacturing, business/management/accounting/finance, and others. It is literally envisioned to be an "all hands on deck" initiative. The resultant models, strategies, and tactics will reflect a new way

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to view and handle materials. These will need to be communicated to stakeholders, which include business people, elected officials and politicians, and numerous other communities. It will be imperative to include nonprofit organizations (e.g., Ellen MacArthur Foundation), NGOs, national laboratories, and other government agencies and the local, state, and federal levels already engaged within the existing circular economy orbit.

Expected Value and Impact:

Numerous positive impacts are expected to be a result of the comprehensive circular economy approach, for example:

- Increasing the sustainability of resources in the local, national, and global levels
- Improving economic opportunities through optimizing the repeated use of materials in different forms, which, in return, circulates economic opportunities and relevant wealth between different communities of consumers, industries, and sellers
- Reducing waste and its related undesired health, economic and environmental problems, emergence of new technologies and creative solutions in multiple parts and sectors of the economy
- Reducing reliance and dependence on petroleum and its derivatives, and
- Tackling looming climate change disasters.

What are the broader impacts of this idea?

Multiple broader impacts will emerge as a result of the comprehensive plan for inculcating a circular economy philosophy, for example:

- Impoverished communities and underrepresented groups and tribes will have an equitable share of the newly emerging economic wealth and technology in addition to lesser exposure to mining and pollution problems that often affect them disproportionally
- Within the national and global level, the atmosphere, soils, and water bodies will be cleaner and more livable for inhabitants
- There will be fewer international and national level conflicts over resources, and
- New job sectors will emerge in the economy with an emerging workforce more open to innovation and collaboration.

What is the reasoning, justification, and/or supporting evidence behind the idea?

Economic and societal forces have enabled the dominance of fossil fuels and other resource extractions for energy and material needs. The linear economy based on these dominating industries has led to the massive accumulation of waste worldwide that threatens all forms of life. The overproduction of plastics and other petroleum-derived products is expected to increase rather than respond to the threats to public health and the environment. The current extraction of resources is not sustainable; fossil fuels and other extracted assets from the earth are non-renewable. A system-wide approach for materials recovery and reuse is required for global supplies of resources for safe and comfortable lifestyles and technological advances. The status quo can only be changed by appropriately valuing used resources and materials, rethinking the life cycles of materials, and recovering and replacing current wasteful production. While many agencies, industries and businesses are moving towards

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circular systems or investigating methods for circularity, the pace is far too slow to address the aforementioned global problems.

The National Science Foundation is the premier agency for the initiation of a rapid transition to a circular economy. NSF supports broad, interdisciplinary programs and projects for science communities. The NSF has the ability to access targeted communities which is required for this work. Moreover, NSF also retains a strong relation with decision makers. Changes in policy will be required for a full and expedient conversion to circular-economy thinking and living.

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7. Sustainable Smart Water Systems (aka Sustainable Water Grid)

What is your Big Idea?

Invest in the development of holistic, multi-scale frameworks for sustainable and smart national water systems that enable climate change resilience through more efficient resource use. Such frameworks will inform economic growth, ecosystem support, policy making, and equity and fair access.

Obstacles/Hurdles/Challenges:

- Climate change is changing the spatio-temporal distribution of water (e.g., precipitation, reservoir levels, frequency and intensity of extreme weather events)
- System of systems: complex interactions between water systems and other systems (e.g., agriculture, food, energy, climate, urbanization, economic growth)
- Social-behavioral-economic-legal (e.g., rights, lawsuits, subsidies, lifestyles)
- Multiple spatio-temporal scales (e.g., watershed, ocean, basin, town/village water supply, season, year, decade)
- Non-stationarity (e.g., future climate is different than past one), Long memory (e.g., reservoirs, aquifers, soil moisture) and teleconnections (e.g, upstream conditions effects downstream) violates key assumptions underlying Machine Learning
- Water grid/system (e.g., rivers/streams, water distribution networks) violates the core assumption of isotropic Euclidean space in spatial statistics
- Uncertainty quantification, predictability, extreme events (e.g., drought)
- Funding to model and study water grid design, engineering, sustainability, resilience, and community-adoption
- Need to coordinate many different types of right holders and user-groups (e.g., industry, federal, communities, farmers) with conflicting interests.

Overall summary of recommendation:

We recommend investment in new research and development of multi-scale frameworks that transform water management in the U.S. through more efficient resource use. Water is a strategic and scarce resource that plays a fundamental role in energy and food production, socio-economic development, ecosystem health, and human survival; as such, water is key to enabling a sustainable and equitable future for all [UN,UN-Water]. However, our aging water infrastructure and management practices have not kept pace with the demands of a growing population and to the emerging impacts of climate change and those are susceptible to significant risk. Specifically, increasing temperatures and shifting weather patterns have increased the severity and frequency of extreme weather events (e.g., floods and droughts) which have led to a wide range of detrimental downstream effects on water quality, cost, and availability, crop and energy production, and overall ecosystem health.

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To address these increasingly urgent challenges within this complex system, we require new innovations that culminate in a nation-wide *Smart Water Grid.* The Smart Water Grid is a set of holistic, coordinated, multi-disciplinary research frameworks that transform our water infrastructure and management practices in the U.S. To enable this, each framework must co-design and integrate advances from math, computing, engineering, chemistry, economics, environmental sustainability, and social science to make resource use more efficient, sustainable, adaptable, and equitably accessible. The applications that these frameworks enable should include those for decision support, inference, modeling and prediction, data analysis and visualization, and intelligent automation that span multiple temporal and spatial scales. The resulting, end-to-end systems should provide measurable benefits including, but not limited to, economic growth, ecosystem support, science-driven government policies and regulations, market-driven pricing of water at its marginal cost, equitable and fair access to resources, and climate resiliency at scale.

What Goal Area(s) does this address?

- Advance scientific knowledge
- Increase climate change resilience
- Anticipate future conditions
- Promote sustainable practices
- Broader impacts and education.

What is required to pursue this?

To pursue this research, we require new investment and engagement in multidisciplinary research and infrastructure, as well as partnership development and stakeholder engagement.

Resources and Infrastructure

Given the complex nature of water systems, the current state of our water infrastructure, and role of water in the food-energy-water nexus, significant funding is needed to bring about the transformation that is needed to build resilience into the U.S. water grid. Funding should be provided to support multiple teams of researchers and students across disciplines and to engage key stakeholders in the effort. We envision a combination of short-term, smaller-scale projects (3-5 years with 3-5 PIs) as well as long-term, large-scale, regional (multi-state) centers (5-10 years, 5-10 PIs). To achieve this ambitious goal will require multiple centers over the next 10-20 years. Part of this investment must include support for and access to various sources of data (e.g., local agricultural water demands, municipal water consumption, climatology datasets, river hydrography data, and rainfall dataset) and research infrastructure for investigation, validation, and demonstration of smart water grid frameworks and applications.

Stakeholder Collaborations

There are a number of key stakeholders of smart water grids that are needed to guide and inform the research, participate in technology transfer, and facilitate adoption. This effort should be led by the multidisciplinary researchers, software developers, data scientists, and students developing the frameworks. These stakeholders include state, local, and federal

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policymakers and regulators, as well as legal analysts with water/energy system expertise who can provide insights into the laws and regulations within which the framework must be implemented. Other stakeholders include industry leaders from water, energy, transportation, infrastructure, and agriculture, among others, who can provide partnerships that help bridge disparate systems, organizations, and locations involved in the food-energy-water nexus, and help develop research prototypes into hardened products for market. Other key stakeholders include independent system operators, utilities, and consumers.

Research efforts will need to be coordinated with existing initiatives such as the National Oceanic and Atmospheric Administration (NOAA) National Water Center. Noteworthy to mention that the Center's missions include flood prediction. The goal of this project is to develop a sustainable water distribution system in response to climate non-stationary status. This can provide valuable resources and historical learnings. It will also be important to involve experts in infrastructure management that have faced similar problems, such as power grid and natural gas networks.

The research collaborations for smart water grid frameworks should include stakeholders with expertise in:

- Theoretical and computational mathematics
- Computing and data distributed systems (including cybersecurity)
- Sensing and data collection (in-situ and remote)
- Hydrology and water chemistry
- Environmental ecosystem sustainability
- Engineering (civil, chemical, electrical, mechanical)
- Economics and Social Science
- Public policy and Law.

Expected Value and Impact:

There are first- and second-order impacts that stem from the research and development of smart water grid frameworks. The first-order impacts are more efficient resource use through better water management and climate change resiliency. The second-order impacts include improved leak detection (e.g., smart water meters, remote sensing, GeoAI to detect and localize leaks) for consumers (inside, outside of residences) as well as for municipal water utilities (Note that approximately one third of municipal water is lost as the result of leaks due to aging pipes, running toilets, etc.). We foresee benefits in terms of science informed policy and gap identification (industry opportunities) in terms of technologies that impede understanding of system behavior and pricing as well as in terms of advances that inform the next strategic investments, e.g., water storage and transport, desalination, etc. A key positive impact of this work is an improved ability to price water at its marginal costs (most efficient) while accounting for fairness/equity (efficient markets are not necessarily equitable). Other impacts include an improved ability to respond to extreme events, to predict the future to make more informed water management decisions, better coordination and data sharing at local, regional, U.S. levels, and ecosystem improvements (including for wildlife, recreation, flood control, and fire protection).

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What are the broader impacts of this idea?

- DEIJ-1: Water Security for all: Access to clean water for drinking and household use (e.g., Jackson, MS; Flint, MI; Appalachia)
- DEIJ-2: reduce disproportionate impact of floods and droughts on disadvantaged community (e.g., those who cannot afford flood insurance)
- Collaboration Nexus: Increase sharing of water-efficiency best practices across "water-similar" communities (e.g., color pellets to detect toilet leaks, aerated showers / sprays, smart water meters/remote sensing to detect leaks, odd/even days for lawn sprinklers, water-efficient lawns, policies, …)
- Outreach (Public, K-12): Increase awareness of, access to and adoption of water-efficiency technology (e.g., EPA watersense certification, leak detection, rainwater harvesting, water-efficient lawns, aerated shower heads and sprays, reuse recycled/greywater for lawns/golf courses, etc.
- Education (Graduate, UG) : Transdisciplinary courses, minors, majors, degrees, curricula to create needed STEM workforce to design, develop, test, and grow the envisaged national water system requiring knowledge of systems thinking, water markets (analogy: TransAmAssoc., FERC, ISO), natural and built water supply (e.g., hydrology, municipal water sub-systems), water demand (public, agriculture, industry, …), demand/supply shaping (e.g., nudging, wireless emergency alerts), control systems, sensing (e.g., smart water meters), data science (e.g., spatio-temporal analytics to detect and localize leaks), policies, laws, regulations, etc.
- Workforce: It will be important to create short training courses, certifications, and training to create/upskill future workforce to manage and maintain the envisaged National water network with needed skills (e.g., grid management to address local/regional imbalances, physical/cyber security)
- Physical/cyber Security: Water grid/system increase the likely risks to distribution networks (e.g., water tower, drinking water supply network) against major threats whether man-made (e.g., terrorism, war) or natural (e.g., toxic algae in Lake Erie affecting Cleveland, Earthquake may rupture pipes or divert/block canals).

What is the reasoning, justification, and/or supporting evidence behind the idea?

Due to climate change and climate variability, e.g., El Niño and La Niña abnormal weather patterns, the temporal variability and spatial distribution of water availability has been dramatically changing. On the other hand, demand for fresh water, i.e., water for agriculture, water for the energy sector, water for the industry sector as well as drinking water, has and will continue to increase driven by population growth, industrialization, and globalization. Indeed, a significant part of the global population is located in areas or regions of high or extremely high fresh water supply risk[1]. Thus, the development of a comprehensive multi-scale water management framework could facilitate the adaptation to climate change and climate variability impacts on water resources. The development of such a comprehensive framework would require fundamental research regarding multi-scale modeling of water

[1] https://www.wri.org/applications/aqueduct/water-risk-atlas/#/?advanced=false&basemap=hydro&indicator=w_awr_def_tot_cat&lat=5.615985819155344&lng=9.843750000000002&mapMode=view&month=1&opacity=0.5&ponderation=DEF&predefined=false&projection=absolute&scenario=optimistic&scope=baseline&threshold&timeScale=annual&year=baseline&zoom=2
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systems in view of a variety of fresh-water resources, diversity of water uses, and temporal and spatial variability of water availability.

Whitehouse OSTP convened a water summit[2] in 2016 stating: "Water challenges are facing communities and regions across the United States, impacting millions of lives and costing billions of dollars in damages. These challenges are particularly problematic in predominantly poor, minority, or rural communities, where water inequality can go hand-in-hand with socioeconomic inequality. Recent events, including record-breaking drought in the West, severe flooding in the Southeast, and the water-quality crisis in Flint, MI, have elevated a national dialogue on the state of our Nation's water resources and infrastructure. This dialogue is increasingly important as a growing population and changing climate continue to exacerbate water challenges. Accordingly, we must work together to build a sustainable water future—one in which everyone has access to the safe, clean, and affordable water they need, when and where they need it."

The power grid management system was restructured in the 2000's in order to meet many challenges that are analogous to those faced by water systems. This gave rise to the emergence of independent system operators that oversee and coordinate markets in specific regions of the U.S. The emergence of coordination has been critical for the reliable supply of power, to improve accessibility, to standardize market procedures, and to accelerate the adoption of emerging technologies. The development of water management systems will have its own unique technical challenges, but we think that the success seen in the power grid can be used to guide the development of policy and best practices.

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[2] The White House Office of the Press Secretary, FACT SHEET: Working Together to Build a Sustainable Water Future, March 22, 2016.

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8. Unraveling the Climate Vulnerability Web: Integration of Physical, Biological, Human Social, and Economic Models in Time and Space

What is your Big Idea?

The climate crisis affects all aspects of society (societal interactions, economics, infrastructure) and the Earth (physical systems of the atmosphere and ocean, ecological and biological systems, etc.); however, traditional methods for investigating the climate problem and finding solutions have often been restricted to investigation of individual physical, ecological, social, or economic silos. Recently, innovative modeling work has spanned a few of these areas, but there is an urgent need to fully integrate climate, social, economic, and ecological models to identify vulnerabilities in human and ecological systems and use that information to manage and reduce climate risks and increase resiliency. **We recommend community-focused research efforts in integrated models of climate, social, ecological, and economic systems.** The end goal of these integrated projects should be for teams to work in concert with community stakeholders so that model output and analysis will be useful for communities currently facing climate impacts. Decision makers and stakeholders will be able to develop recommendations and policies to adapt to and mitigate climate change vulnerabilities in these communities.

Conceptually, integrated modeling frameworks are currently instantiated in the form of integrated assessment models (IAMs); however, current implementations are often underdeveloped, leaving them limited. The current versions of these models frequently neglect important aspects of social and natural systems—such as social and ecological feedback and ecosystem responses—in the model development and analysis in favor of focusing on aggregated economic outcomes. Furthermore, they are primarily focused on (new) stationary or equilibrium states of the integrated system, which is an insufficient framework for understanding responses to human-driven climate change. Advances in understanding transient behavior through studying complex, nonlinear nonautonomous systems have shown us that **understanding the path to a new equilibrium can be more important than the final equilibrium state**.

We recommend the development and integration of high-resolution models focused on regional and smaller spatial scale and/or conceptual models that describe general nonlinear relationships in a system. These models can be developed and analyzed in small, multidisciplinary teams. This is in contrast with high-dimensional models such as general circulation models (GCMs) or earth system models (ESMs) which require large groups, resources, and longer completion period at national labs for the development and analysis, and would be more appropriate in a global digital-twin framework.

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What Goal Area(s) does this address?

Our recommendation will create and advance scientific knowledge in mathematics, climate science, social science, economics, sustainability, adaptation, and resiliency. Mainly, it will increase climate change resilience, anticipate future conditions, achieve more sustainable practices, and outreach and educate stakeholders. Also, it will assist policy-makers in developing and evaluating potential policies to reduce risk in social and ecological systems.

What is required to pursue this?

Expertise from multiple mathematical subdisciplines (dynamical systems, numerical analysis, simulation, machine learning, statistics, uncertainty quantification), and other STEM (computer science, environmental science and ecology, atmospheric, land, sea ice and ocean science, agricultural science) and social science disciplines (economics, behavioral science, and political science) is required, as well as input from stakeholders (local and regional government officials, community educators, policy makers, NGOs, and entities in the private sector).

Typical funding structures break grants up, passing the pieces on to individual teams that pursue parts of the project and will not lead to the required interconnections among the different teams. This will inhibit the kind of integrated multidisciplinarity required for the projects recommended. We recommend the development of an **innovative and appropriate funding and governance mechanism** for the overall research effort. An example would be a virtual center that supports the necessary collaborations and coordination among groups and individuals with the required different expertise, including ensuring coherence among different research efforts. This virtual center would be responsible for identifying candidate communities, outreach, and coordination of model development and data gathering.

Expected Value and Impact:

The expected developments and values of this program span research disciplines, international government policy, and decision-making.

The proposed recommendation of model development and coupling is a tried-and-true paradigm for describing climate processes; in essence, a climate model is a coupling of submodels representing physical and chemical processes governing the atmosphere, ocean, land, cryosphere, and more. **Here, we recognize the gap between the individual output of these physical models, and the goals that we wish to achieve, particularly regarding model coupling for assessing and reducing vulnerability.** We identify key missing actors as biological ecosystems, economics, social attributes, and human behavior and propose that models describing these biological and social systems are essential groundwork for robust modeling, forecasting, decision-making, and policymaking centered on vulnerability.

One benefit of model coupling is in identifying emergent phenomena (e.g. hysteresis loops, tipping points, feedbacks, and cascades) which can only be revealed through coupling disparate subsystems, and thus represent critical obstacles hampering our ability to make predictions from real nonlinear systems with the additional challenge of temporal changes. **In closing the distance between models and metrics for vulnerability assessment, we**

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form a (far more) complete picture of attribution pathways from computational and mathematical modeling decisions, ecosystem services, social vulnerabilities, and human consequences. From this, comprehensive quantified uncertainty in forecasts (that can be attributed to processes covered by modeling) may be captured. Knowledge of uncertainty can lead to targeting resources to key aspects of model development, and targeted data acquisition, which leads to quantifiable uncertainty reduction for assessments. Such developments build greater scientific understanding on climate change vulnerability.

Substantial challenges arise from the integration of models of social, biological, and physical sciences. There are substantial quality, spatio-temporal scale, and accuracy differences among the models and data between disciplines, requiring new developments from multi-fidelity modeling where data are sparse, or use of data-driven approaches where models are lacking. Also, the relative diversity and accessibility of data are an obstacle. It is likely that key developments of data-assimilation and machine learning will be required to incorporate data from all relevant sources, as well as new platforms and application programming interfaces (APIs) for handling universally standardized interaction of data-sets to preserve openness.

What are the broader impacts of this idea?

The impacts of climate change have broad-reaching repercussions that cut across global systems, both social and ecological. Managing social, economic, and ecological vulnerabilities is a core aspect of national security, as the effects of adverse events can quickly escalate. For example, climate change-induced drought may result in mass migration from rural communities to urban areas, and the movement of neglected, tropical, and vector-borne diseases to new communities can increase vulnerability of poor communities, both leading to political and social unrest. A science-based understanding of vulnerability also contributes to climate justice, as women and underserved communities often bear a disproportionate burden of climate change impacts. These efforts will naturally require outreach to focal communities, both to solicit data as well as to communicate the findings of these studies to get public buy-in. Students involved in the necessary research will get firsthand experience working on a multidisciplinary team with significant social, economic, and environmental implications. Also, assisting the development and evaluation of policies with cross-disciplinary communication and scientific foundations are essential for implementing actions to adapt to and mitigate the effects of climate change.

What is the reasoning, justification, and/or supporting evidence behind the idea?

Today, communities worldwide are struggling with the complex interaction of environmental threats, economic development, and societal inequity. These threats also impact the ecosystems on which these communities rely. Both human and ecological communities face interconnected risks that necessitate the use of a data collection and an approach that can assess these impacts through a holistic lens.

For ecological communities, the data on hazards, exposure, and vulnerability that is used to calculate risk, is sparse and incomplete. While data on hazards and exposure of human communities is becoming more widely available, data on their vulnerability remains limited. Policymakers need city- and region-specific data to best understand their levels of risk and

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engage in effective adaptation planning. Where data is sparse, the generalizability of modeling off of data is invaluable to cover the shortfalls.

Climate adaptation finance remains limited, despite it being recognized as a global priority (Climate Policy Initiative, 2018). This is partly explained by a lack of comparable data and tools which illuminate complex climate change impacts, and a lack of evidence that national adaptation planning is being sufficiently downscaled into subnational planning to address growing climate change risks (United Nations Environment Program, 2021).

NSF is uniquely positioned to bring together interdisciplinary teams due to its broad funding scope. Further, NSF has a successful history of programs that transcend the standard funding mechanisms of PI-driven funding, with the GLOBEC program a particular example. This type of funding structure is uniquely possible at NSF and is needed to leverage the expertise of STEM and social science researchers and community stakeholders. When these diverse teams co-produce the research questions, analysis, and output, they will build the foundations of a new transdisciplinary approach to identify climate risks and mitigate vulnerabilities.

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9. Change the Conversation at the Local Level

What is your Big Idea?

While there is abundant climate, energy, transportation, and commodity data, along with synthesis results such as, for example, predictions of short-term weather events, the means to distill this information in a reliable and contextual way to an individual is limited. Further, individual actions that can benefit the climate are limited by a lack of this distilled information, and are threatened by the promotion of misinformation from various media and social media outlets. In addition, there is a need to provide a trusted analysis of these data streams so that community leaders and decision makers can assess the cost and benefits of decisions related to climate risk to the community. A means to support community leaders and decision makers in these choices is critical for population buy-in to the difficult decisions related to climate mitigation and adaptation.

Our suggestion is to develop multiple interdisciplinary centers that focus on two aspects to resolve these concerns: i) developing a mathematical and computational framework to evaluate novel metrics of data streams, and ii) building a community network of local decision makers, community leaders, and the local population to evaluate how local community behavior is modified by these new metrics, which can inform the development of appropriate incentives to improve climate mitigation behaviors. Only through the combined efforts of mathematical and behavioral scientists can we find out what incentives are required to promote decisions that combat climate change. Mathematical research opportunities are varied in the selection of relevant data streams and the relevant analysis. Additional modeling can be considered on the validation through significant survey sampling over a local region, which can address with social scientists open behavioral questions such as the quantification of irrationality. This collaboration allows for the opportunity to overcome the restrictive assumptions currently found in state-of-the-art behavioral models.

These centers have the potential to promote interest in mathematical, physical, and behavioral sciences, and are well-suited for outreach activities in K-12 environments.

What Goal Area(s) does this address?

- Promote sustainable practices
- Anticipate future conditions
- Increase outreach and broader impacts
- Accelerate clean energy innovations
- Advanced mathematical/behavioral science knowledge.

What is required to pursue this?

We conservatively request $125 million for the establishment of five Multidisciplinary Climate Change Research Centers across the United States. This fund will provide $ 5 million per center for 5 years. Five centers will be located across the United States. These centers aim to help scholars in various disciplines such as mathematics, statistics, social science, engineering, etc., collaborate efficiently and effectively with community stakeholders for understanding human behavior. Subsequently, outcomes of such studies should be implemented for promoting climate change mitigation and adaptation measures at the local level. These centers will provide resources for researchers to conduct high-impact multidisciplinary research in modeling human behaviors given the uncertainty climate change imposes on society.

In terms of innovation - fundamental advances must be made in the mathematical modeling of communities as they respond to dynamically varying information streams. In this case, responses may be instances of migration, policy adoption or abandonment, resource consumption and allocation, social media presence. By building such models, calibrating them with socioeconomic data, and endowing them with interpretable qualities - decision makers can be advised to devise policy initiatives that capitalize on information streams for maximal community engagement with a climate change mitigation or preparedness process. Mathematics can engage with domain and social sciences by building on past successes of agent and simulation-based models for computational social science by leveraging big data streams, advanced machine learning algorithms, progress in uncertainty quantification, etc.

Expected Value and Impact:

The establishment of five geographically diverse, interdisciplinary research centers focused on *developing mathematical models that foster sustainable communities* will create the means for mathematicians, social scientists, community leaders and other stakeholders to work together toward complex societal issues by formulating them as mathematical problems, while eliminating biases toward historically underserved, vulnerable communities. The development of novel mathematical models that are equitable and just, and hence deliver trustworthy information, will support community leaders and other stakeholders in making well-informed decisions that benefit the entire community. The novel models will ingest heterogeneous data from diverse sources, including but not limited to climate, transportation, energy, water, and food sectors, and will provide actionable information that will enable the creation of software platforms and other technologies that will overall increase sustainability and resilience of our communities.

What are the broader impacts of this idea?

The outcomes of this solicitation will be shared with decision-makers at the local level. The decision-makers can take the findings and implications regarding human behaviors into consideration when implementing climate change mitigation and adaptation measures at the local level. Practitioners (e.g., public managers) will be able to utilize the implication of the proposed studies to facilitate the implementation process of climate change mitigation and adaptation policy options.

The proposed studies can be shared with K-12 students for education purposes. Students will learn how the original data sources related to climate change are found, careers in science, economics, math, and other disciplines, how to recognize methods of social manipulation, and how government labs/agencies are central in the data collection and validation. Furthermore, the proposed research projects provide opportunities for

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undergraduate and graduate students for learning and working in math modeling, survey collection, etc.

The proposed studies of this solicitation will focus on the diverse communities with respect to income, race, and ethnicity, and population density. The findings and implications will be utilized to serve marginalized and more vulnerable communities in the United States. We seek to avoid the "one size fits all" strategy which may adversely affect certain communities in the path to climate change adaptation and mitigation.

Therefore, a diverse group of researchers will participate in projects to identify potential inequity and disparity issues with any proposed algorithms or datasets to ensure equitable outcomes for various communities.

What is the reasoning, justification, and/or supporting evidence behind the idea?

With the growing threat of climate change, scientists and decision-makers have proposed various policy options that may mitigate the causes of climate change. However, optimal climate change mitigation and adaptation are unlikely to occur through the introduction of scientific information and policy options. These policy options should be implemented at the different levels of society from the global level to the individual household level.

In particular, there are several instances of communities and individuals who act against their best economic or health interests. Social behavior has both a rational and irrational element and it is important to try and understand this mathematically for making scientific recommendations to improve resiliency and sustainability in communities. By developing models which can explain the behavior at a local level, policy recommendations from scientific research can be transformed more efficiently to action. More importantly, recommendations can be tailored to various levels of the community (individual, county, state, etc.) to optimally influence national outcomes.

The broad interest between mathematical and behavioral sciences, and the necessary interdisciplinary work is well within the mission of NSF. The NSF has a history of supporting disciplinary and multidisciplinary centers in mathematics, manufacturing, and big problems in industrial processing. The organizational framework within NSF makes it the ideal agency to assess the variety of research proposals to be submitted and to evaluate the progress and performance of these research centers after funding.

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Jordan	Kirk	IBM Research
Kaper	Hans	Georgetown University

Krintz	Chandra	University of California, Santa Barbara
Lehner	Flavio	Cornell University
Li	Tongtong	Dartmouth College
Lin	Guang	Purdue University
Liu	Chun	Illinois Institute of Technology
Maulik	Romit	Argonne National Laboratory
Nadeau	Alice	CH Robinson Worldwide, Inc
Nadeau	Lou	Eastern Research Group, Inc.
Netto	Marcos	National Renewable Energy Laboratory (NREL)
Peller	Julie	Valparaiso University
Peszynska	Malgorzata	Oregon State University
Pothen	Alex	Purdue University
Powers	Susan	Clarkson University
Quaini	Annalisa	University of Houston
Reimer	Jody	University of Utah
Rouleau	Tracy	TBD Economics, LLC
Ruiz-Mercado	Gerardo J.	U.S. Environmental Protection Agency
Schwarz	Udo	Yale University
Shekhar	Shashi	University of Minnesota
Tavakoly	Ahmad	US Army Engineer Research and Development Center
Tilley	Burt	Worcester Polytechnic Institute
Watson	Campbell	IBM Research
Weekes	Suzanne	SIAM
Yetman	Greg	Columbia University
Zavala	Victor	University of Wisconsin-Madison