Research and Education Priorities to Address Climate Change, Boost Environmental Resilience, and Advance Clean Energy

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The Society for Industrial and Applied Mathematics (SIAM) presents the following recommendations for Congress and federal agencies on areas of research and education related to climate change, environmental resilience, and clean energy that would benefit from involvement of the applied mathematics and computational science community. SIAM is an international community of over 14,000 members from academia, industry, and government. Members come from many different disciplines, but all share an interest in applying and developing state-of-the-art techniques of mathematics and computational science to solve real-world problems.

Background and Justification

Now is a critical time to leverage mathematics and computational science to understand climate change phenomena and advance effective mitigation efforts. The disciplines that SIAM represents enable modeling of natural phenomena and complex infrastructure to better understand risk and resilience for decision-making, creation of tools for computational design to speed technology innovation, and development of control technologies to enhance smart systems. Together these areas are critical components of the effort to confront the climate change challenge. Climate change necessitates research to anticipate future conditions, accelerate clean energy innovations, and increase our nation's resilience. The SIAM community stands ready to contribute to needed research and education efforts. Research and training that advances interdisciplinary collaboration is important to develop robust solutions to these complex challenges. Federal agencies should also look to partner to enable these collaborations and bring modeling, analysis, and optimization expertise to the forefront to enhance an array of climate-related efforts. Federal support is central to continued innovation and mitigation.

This report was prepared by a task force established under the SIAM Committee on Science Policy (CSP) including a diverse group of experts from academia and national laboratories. Its contents were also informed by separate information gathering activities. The report contains recommendations for the Administration; research agencies such as the National Science Foundation (NSF), Department of Energy (DOE), United States Department of Agriculture (USDA), National Oceanic and Atmospheric Administration (NOAA), Department of Transportation (DOT), National Institutes of Health (NIH), Department of Defense (DOD), and others addressing climate and energy research; and congressional leaders and others overseeing these efforts.

Overview of Recommendation Categories

Based on survey responses and internal discussions, SIAM's findings and recommendations are organized into four categories:

Climate and Earth System Prediction – This includes modeling, simulation, and optimization; improved computational capabilities; innovation rooted in basic research, such as development of statistical methods and computational algorithms for monumental volumes of diverse environmental data; and support for research in areas like dynamical systems, optimization, and stochastic modeling to help understand levels of possible prediction, characterize uncertainty, and improve forecasting capabilities.

Resilient Communities and Environmental Justice – Applied mathematics and computational science provide the tools to explore and evaluate scenarios designed to protect communities and critical infrastructure from extreme events like sustained periods of drought, shifting precipitation patterns, and impacts of rising ocean levels. Equally important is that these tools can enable and inform more equitable decision-making that addresses existing economic, racial, and other disparities and ensures that the impacts of climate change do not fall disproportionately on communities that are already marginalized. Algorithm and model development, data analysis, and computational simulation enable evidence-based choices despite the uncertainty of the future. Applied mathematics and computational science can help us better understand the many consequences of climate change. These include various community-level impacts, socio-economic effects, as well as regional and global conflicts and migration patterns due to climate change.

Clean Energy Innovation – Efforts to accelerate energy innovation to reduce emissions are of tremendous interest across the federal government and will need to incorporate contributions from applied mathematics and computational science. Intersections with energy production and use fall in two different contexts. The first is the reliable, resilient, and economic planning and operation of the future grid, including the integration of renewables, thereby making our power delivery system stronger, more flexible, and decarbonized. The second is that applied mathematics and computational science are also involved in the development of the technology itself from materials for batteries and hydrogen storage to the design and placement of offshore wind to the transformation of transportation.

Workforce Development – Climate change presents complex challenges, and to address them it is essential that we prepare mathematics and computational science students to work effectively on diverse, multidisciplinary, convergent teams, including with social scientists. The climate workforce of the future must be equipped with robust mathematics, computational science, statistics, and other science, technology, engineering, and mathematics (STEM) skills to innovate and address climate issues. Therefore, it is important to continue and grow federal investments to support mathematics, computational science, and interdisciplinary STEM education.

Detailed Recommendations

Climate and Earth System Prediction

The federal government has already made significant investments and put in place robust research funding to collect climate data and use climate modeling to assess the anticipated impacts of climate change. These efforts are time sensitive and should continue, but the demand for more accurate predictions will grow significantly over the next few years and decades. Applied mathematics and computational science have a critical role to play in meeting this demand. The applied mathematics and computational science community has the expertise and capacity to lay the groundwork and expand current efforts for a more robust climate modeling and Earth system prediction capability. Mathematical, computational, and climate science research and modeling will be critical to understanding how climate change will impact human systems, improve decision-making amid uncertainty, and strengthen the resiliency of all communities. Greater investment will be needed in the following research areas to realize these goals:

- Integration of human behavior into new and existing models, for example, addressing the impacts of major societal upheavals and migrant flows on climate prediction and incorporating policy impacts such as those affecting major food systems;
- Increased collaboration and input of applied mathematics and computational science in the quantification of modeling uncertainties, which is essential to understanding the quality of our knowledge about future climate change and the range of risk we are facing;
- Production of digital twins of specific physical systems, such as urban areas, forests, or agricultural land, to enable better understanding of the impact of certain policies under various scenarios;
- Advances in coupled and multi-scale modeling approaches to better integrate dynamics from clouds, oceans, cities, food systems, and other aspects of the whole Earth system;
- Increased modeling and prediction of local and regional climate impacts to enhance understanding of risk and resilience measures; and
- Data management and integration tools to advance incorporation of the enormous amounts of data flowing from Earth observations to enhance modeling and prediction.

The task force notes that the list of research topics above is not meant to be exhaustive but captures major challenges. Across these areas, interdisciplinary collaboration will be essential to combine applied mathematics and computational expertise with that from the atmospheric, oceanic, and geosciences; social and behavioral sciences; and biological, agricultural, and ecological sciences. Interagency partnerships can facilitate these collaborations, for example, to better connect the applied mathematics and computational science community, primarily supported by NSF and DOE, to major modeling and observation efforts at NOAA, other parts of DOE, NASA, etc. NSF should seek to promote convergent research across the communities that it supports in all of the aforementioned research areas, which would be consistent with the budget request's proposed increases to NSF's U.S. Global Change Research Program (USGCRP) efforts. NSF should encourage alternative modes of collaboration, in addition to the traditional focused research groups and institutes. Online platforms enable collaborations in virtual interdisciplinary departments which are geographically distributed and include theoretical scientists as well as application experts. This model was successfully implemented in 2011 in the Mathematics and Climate Research Network (MCRN); the MCRN brought together mathematicians and geoscientists to spur the participation of mathematics in climate research. Core research in applied mathematics and computational science is additionally required to ensure continued innovation in fundamental tools and sustainment of the applied mathematics and computational science ecosystem.

Resilient Communities and Environmental Justice

Applied mathematics and computational science tools like algorithm and model development, data analysis, and computational simulation help us anticipate future scenarios to enable more informed and equitable decision-making. NSF and DOE partnerships with USDA, DOT, the Forest Service, U.S. Agency for International Development (USAID), Department of Homeland Security (DHS), DOD, NIH, and other agencies responsible for climate adaptation and resilience could enable better decision-making tools for critical national infrastructure and facilities, farmers, cities, and other stakeholders that must be able to interpret local risk, translate complex information to usable knowledge, and build resilient infrastructure. Applied mathematics and computational science should be leveraged to measure resiliency to better understand and mitigate risks.

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- Funding for the applied mathematics and computational science community is not widely available to contribute to research on resilient communities and environmental justice, and researchers do not know where to receive funding for such work, especially research that centers on individual communities. Federal research agencies should coordinate and increase investment in this critical and timely area of research.
- Mathematicians and computational scientists are experts at quantification, and tools like modeling can be used to develop resiliency indicators. With such information, investments could be targeted to areas with gaps in resiliency capabilities.
- Mathematics and computational science can be used to assess environmental disparities. These findings help enable action to be taken to ameliorate related inequalities. Federal research agencies should consider where it would be beneficial to require research on disparities and environmental justice as part of successful awards. Additional dedicated research solicitations should be offered which focus on environmental-related disparities and evidence-based solutions.
- The task force is enthused to see the new Civic Innovation Challenge (CIVIC) program at NSF support research that originates from community-identified issues. NSF should expand support for research that address challenges put forward by community stakeholders. The task force hopes to see additional investment in resilience and environmental justice from NSF's proposed Translation, Innovation, and Partnerships (TIP) effort. NSF should seek to build research understanding and increase training on strategies for community engagement, advance use inspired research towards societal needs, and spur social entrepreneurship. An example might be to create an I-Corps-like program for social engagement that teaches faculty how to find community stakeholders and build equitable, inclusive partnerships that make a real difference for communities.
- Farmers and other individual stakeholders must increasingly make decisions based on future climate risk, yet often do not have access to decision-making tools or ways to interpret complex data. USDA should build on its successful extension model to connect farmers and rural communities with applied mathematicians, computational scientists, and data scientists who can help agricultural and rural stakeholders use data and modeling tools to enable informed decisions and help rural communities build resilience for a changing future.
- Agencies including the Federal Emergency Management Agency (FEMA) and Environmental Protection Agency (EPA) offer environmental resilience grants (Building Resilient Infrastructure and Communities (BRIC) and Environmental Justice grants respectively), but these are not open to academic researchers directly. Research is needed to better understand environmental resilience and environmental justice challenges and build better tools to address future needs. DHS and EPA should ensure that at least a small part of these programs enable future-oriented research and academic partnerships.
- Policymakers must make critical decisions with limited information on rapid timescales. NSF should support collaborative research between mathematicians, computational scientists, and social scientists to advance understanding of group dynamics and decision-making in the presence of uncertainty, and to incorporate the influence of social behavior into mathematical models. Predictive science also needs to be advanced to better understand future risks and enable better planning. There needs to be an increased emphasis on the interpretation and communication of uncertainties. The DOD Minerva program also plays an important role in understanding societal risks from environmental changes. DOD should seek to incorporate computational approaches and continue basic research efforts to enhance our ability to model social and behavioral systems.

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- NSF should continue to fund convergent, cross-cutting, and NSF-wide partnerships to address research related to climate change resilience. Partnerships between mathematical- and computational-focused parts of NSF and every other directorate are valuable. One gap where much more could be done is partnerships with the Directorate for Social and Behavioral Sciences (SBE), which sits at the center of many of the decision-making and behavioral questions and where modeling tools and understanding are underdeveloped relative to other fields. NSF should also seek to fund convergent research to advance resilience and build on past models such as the Critical Resilient Interdependent Infrastructure Systems and Processes (CRISP) program.
- DOE should seek to incorporate applied mathematics and computational science research when carrying out new initiatives such as the proposed Urban Integrated Field Laboratories that would rely on integrated models and tools to improve understanding of the natural and human components of the climate system.
- USDA should seek to incorporate applied mathematics and computational research to compliment new research initiatives aimed at climate smart agriculture proposed in the President's budget request.
- NIH should seek to incorporate applied mathematics and computation research when addressing climate change and its impact on health, a program of increased priority in the fiscal year (FY) 2022 budget request.

Clean Energy Innovation

While the federal government has made significant research investments into clean energy and overseen the steady expansion of the U.S. renewable energy sector, continued investments into new and innovative research are essential in the transition to a clean energy future and to combat the effects of climate change. At the same time, the present situation offers an opportunity for the applied mathematics and computational science community to assist in the research and creation of innovative clean energy technologies. Modeling and simulation can greatly assist in the development of new technology to understand complex systems for technology integration, speed design efforts, model new materials to create better functionality, advance manufacturing to increase scale and lower costs, and enhance control to enable smart systems.

- DOE has a major role to play in the development of new clean energy technologies. Much of this investment happens through the DOE Applied Energy programs, but these programs have comparatively less engagement with the applied mathematics and computational science community than other parts of DOE's research enterprise. DOE should seek to spur new collaborations such as through the Scientific Discovery Through Advances Computing (SciDAC) program to address clean energy challenges and spur technology development.
- DOE should expand efforts that connect the applied mathematics and computational science community to basic energy research, such as through SciDAC partnerships with the Office of Basic Energy Sciences and the Computational Materials Sciences Centers. For example, partnerships could enhance research needed to understand the mathematics to simulate new battery chemistries and catalysts for hydrogen.
- NSF should expand funding for convergent research between the applied mathematics and computational science communities with those in materials science and engineering to enable foundational advances in materials for clean energy, energy systems, manufacturing, and efficient devices.

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- Federal support for education and training in optimization, control, and connections to clean energy system operation, vehicles, buildings, and materials science will help create the workforce needed to advance clean energy research.
- DOE should leverage significant investments from the Exascale Computing Program (ECP), which has developed multiple applications and software tools focused mathematics and computational science advancements, for clean energy innovation.
- DOD should seek to incorporate applied mathematics and computational approaches in reducing the Department's energy demand and basic research to combat climate change challenges – areas of priority in the President's budget request.

Workforce Development

To address the topics above, workforce development is essential to prepare researchers that can work on convergent challenges, connect with key stakeholders and address their needs, and build better connectivity between communities that do not have a long history of working together. We must prepare applied mathematicians and computational scientists to work effectively on multidisciplinary, collaborative teams, including with social scientists, to address complex challenges presented by climate change. The climate workforce of the future must be equipped with robust mathematics, computational science, statistics, and other science, technology, engineering, and mathematics (STEM) skills to innovate and address climate issues. Federal investment in traineeships and efforts to enhance undergraduate and graduate education are essential to achieve these goals.

- NSF should continue to support innovations in graduate education for both discipline specific issues and to build better training for convergent research. NSF Research Traineeships and Innovations in Graduate Education are good examples of these programs and should be expanded. Math-specific programs such as the Research Training Groups in the Mathematical Sciences should prioritize training efforts that give students convergent research experiences and skills. Federal agencies should also continue to support graduate education through fellowships such as the NSF Graduate Research Fellowships, the DOE Computational Science Graduate Fellowship (CSGF), and the DOD National Defense Science and Engineering Graduate Fellowships. These programs support excellent students and give them independence to explore new areas.
- The DOE CSGF program funds a number of fellows in atmospheric and Earth sciences and helps to maintain the pipeline of the computationally trained mathematical workforce. Researchers trained in computational science and working in universities, national laboratories, and industry are central to DOE's mission and essential to propel advances in DOE mission-critical fields such as nanotechnology, biofuels, genomics, and materials fabrication. CSGF helps ensure the existence of an adequate supply of scientists and engineers with strong computational research experience and close ongoing ties to DOE to meet national workforce needs to address climate change. DOE should ensure that students studying environmental and applied energy challenges are participating in the program.
- NSF and other federal agencies should support training researchers and students to engage with stakeholder communities including non-profit organizations. Collaborations with stakeholders are already encouraged, but training is needed to build relevant skills. Academia must also place value on community engagement and interdisciplinary collaborations when assessing tenure and promotion. As mentioned above, programs could be modeled after NSF's industry collaboration and entrepreneurship programs, but with the goal of connecting researchers to

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community groups, non-profit stakeholders, and municipalities. This should be a major focus of the new Translation, Innovation, and Partnerships effort.

- The scientific community as a whole, including the applied mathematics and computational science disciplines specifically, must improve their ability to effectively communicate to the general public the problems, risks, and mitigation opportunities associated with climate change. NSF and other agencies should consider initiating and funding training programs for young researchers to become effective science communicators. The NSF Mathematics Institutes could be leveraged for this purpose.
- Federal research and education agencies should explore ways to incentivize universities to overcome silos and offer interdisciplinary course offerings and support interdisciplinary research. NSF should increase investment in programs such as Improving Undergraduate STEM Education (IUSE) that enable curricular innovations and implementation of proven models to enhance undergraduate courses. The Division of Mathematical Sciences (DMS) should also explore whether to engage in focused undergraduate programs such as those undertaken by the Directorates for Geosciences (IUSE-GEOPATHs) and Engineering (IUSE-RED).
- The COVID-19 pandemic has caused major disruption to collaborative efforts such as workshops and conferences. These activities play an essential role in bringing researchers together and building new connections. As we emerge from the pandemic, federal agencies should seek to fund more interdisciplinary workshops and conferences and build back this incredible resource for our innovation ecosystem.
- NSF and NIH should use their post-doctoral support to encourage interdisciplinary training, acquisition of computational and data science skills, and time spent with mentors in other disciplines or in practicums with other agencies.
- NSF and other agencies should institute funding for training networks that bring together researchers at different institutions, including universities and national laboratories. These enable graduate students to learn from a broader variety of mentors than are present on a single campus and can effectively expose the students to leading experts. Such networks have been very successfully used in Europe to supercharge a new or growing area, particularly in the climate arena.
- Federal research agencies should continue to support graduate and undergraduate internships that expose students to new challenges and areas of research and application. It is essential that these programs include applied mathematics and computational science students. Non-Academic Research Internships for Graduate Students (INTERN), Mathematical Sciences Graduate Internship (MSGI), and other programs that build connections between universities and federal labs and industry are critical to building a federal workforce to address climate challenges. NSF should seek to build on these programs or adapt new mechanisms to support these pathways. It would also be useful to encourage participants to share their experience and new connections with their home institutions to amplify the impact of these internships on university researchers beyond the initial participants.
- NSF should scale up programs that connect academic researchers and industry such as the Grant Opportunities for Academic Liaison with Industry (GOALI) program. However, many academic researchers find it challenging to take the first step of finding an industrial partner. NSF could help address this situation by creating a clearing house or other mechanism to help researchers find interested industrial partners, including small businesses tackling clean energy, and to help industry find partners to address their challenges.
- NSF should incentivize mathematicians and computational scientists to learn a completely new discipline or to explore new synergies and advance climate innovation. Programs such as

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Research Initiation in Engineering Education could serve as models for how to build a practice of researchers taking risks and building on their knowledge base to address new challenges.

- Climate change has disproportionate impacts on under-represented and under-served groups. It is imperative that NSF expand its focus on broadening participation. The Inclusion across the Nation of Communities of Learners of Underrepresented Discoverers in Engineering and Science (INCLUDES) initiative is a powerful model that could be expanded for this purpose. NSF should also look to create an ADVANCE-style program for under-represented minority faculty, which is a critical missing piece of its broadening participation portfolio. NSF should carefully assess its review process and other policies to root out bias and build transparency.

APPENDIX A

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APPENDIX B

Recommendations by Federal Agency:

Department of Energy (DOE):

- DOE should seek to spur new collaborations such as through the Scientific Discovery Through Advances Computing (SciDAC) program to address clean energy challenges and spur technology development.
- DOE should expand efforts that connect the applied mathematics and computational science community to basic energy research, such as through SciDAC partnerships with the Office of Basic Energy Sciences and the Computational Materials Sciences Centers. For example, partnerships could enhance research needed to understand the mathematics to simulate new battery chemistries.
- DOE should ensure that students studying environmental and applied energy challenges are participating in the Computational Science Graduate Fellowships (CSGF) program.
- DOE should seek to incorporate applied mathematics and computational science research when carrying out new initiatives such as the proposed Urban Integrated Field Laboratories that would rely on integrated models and tools to improve understanding of the natural and human components of the climate system.

United States Department of Agriculture (USDA):

- USDA should partner with NSF and DOE to address climate adaptation and resilience and enable better decision-making tools for farmers and other stakeholders that must be able to interpret local risk and translate complex information to usable knowledge.
- USDA should build on its successful extension model to connect farmers and rural communities with applied mathematicians, computational scientists, and data scientists who can help agricultural and rural stakeholders use data and modeling tools, enabling informed decisions and helping rural communities build resilience for a changing future.
- USDA should seek to incorporate applied mathematics and computational research to compliment new research initiatives aimed at climate smart agriculture proposed in the President's budget request.

National Oceanic and Atmospheric Administration (NOAA):

- NOAA should pursue interagency partnerships to better connect the applied mathematics and computational science community to its major modeling and observation efforts.
- NOAA should seek to incorporate applied mathematics and computational research into programs dedicated to combatting climate change challenges, particularly as such programs are proposed for substantial growth in the FY 2022 budget request

Department of Transportation (DOT):

- DOT should pursue interagency partnerships to better connect the applied mathematics and computational science community to areas regarding climate adaptation and resilience that could enable better decision-making tools for critical national infrastructure and facilities, farmers, cities, and other stakeholders that must be able to interpret local risk, translate complex information to usable knowledge, and build resilient infrastructure.

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National Institutes of Health (NIH):

- NIH should use post-doctoral support to encourage interdisciplinary training, acquisition of computational and data science skills, and time spent with mentors in other disciplines or in practicums with other agencies.
- NIH should seek to incorporate applied mathematics and computation research when addressing climate change and its impact on health, a program of increased priority in the FY 2022 budget request.

Department of Defense (DOD):

- DOD should seek to incorporate computational approaches and continue basic research efforts to enhance the ability to model social and behavioral systems.
- DOD should seek to incorporate applied mathematics and computational approaches in reducing the Department's energy demand and basic research to combat climate change challenges – areas of priority in the President's budget request.

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