Climate Intervention in an Earth Systems Science Framework: A Workshop

Briefing Book

Virtual Workshop

June 20 and 22, 2023

NATIONAL ACADEMIES Sciences Engineering Medicine

BRIEFING BOOK
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Meeting Information

NATIONAL ACADEMIES Sciences Engineering Medicine

Climate Intervention in an Earth System Science Systems Science Framework: A Workshop

Climate intervention techniques are increasingly technically feasible, but remain highly controversial due to their transboundary nature, their risks of unintended harmful impacts, and the presence of fundamental ethical concerns. Advancing understanding of the potential efficacy, cascading environmental and social impacts, and societal acceptability of climate intervention requires broad public engagement and ongoing collaboration across a diverse spectrum of expertise.

This virtual workshop draws on the recent National Academies report *Next Generation Earth Systems Science at the National Science Foundation* to present climate intervention as an integrative but expansive framework, encompassing both natural and social processes. This convening will create a dialogue covering the human, physical, and technical dimensions of climate interventions, and will situate these considerations within the context of convergent research and the capacities of the National Science Foundation.

TUESDAY, JUNE 20, 2023 **Click Here for Q&A**

*All time is in Eastern Daylight Time (EDT)

11:00–11:15 **Welcome and Purpose of the Workshop**

Jim Hurrell, Chair of Workshop Organizing Committee

11:15–1:25 **Session 1: Cross Cutting Issues, Needs and Opportunities**

This session will frame the discussion of climate intervention from both a human dimensions perspective, and a physical sciences perspective. Participants will discuss research design, how to assess risk (relative to the risks of climate change), navigating societal & physical systems implications, unintended consequences, natural-social system interactions, as well as the essential need for governance research. Additionally, earth systems predictive capacity, current observation and monitoring infrastructure, as well as scalability and readiness of different techniques will be considered. This session will present key concepts and frameworks to inform how the following sessions consider specific techniques and applications.

Welcome, Framing Remarks
Manjana Milkoreit, Session Chair

Human Dimensions Keynote
Holly Buck, University of Buffalo

Human Dimensions Panel
Jane Flegal, Stripe
Philip Macnaghten, Wageningen University
Juan Moreno-Cruz, University of Waterloo
Simon Nicholson, American University
Christopher Trisos, University of Cape Town
With Q&A

Physical Dimensions Keynote
Ken Caldeira, Stanford University

Physical Dimensions Panel
Michael Diamond, Florida State University
Forrest Hoffmann, Oak Ridge National Laboratory
Ben Kravitz, Indiana University
Katherine Romanak, The University of Texas at Austin
Pete Smith, The University of Aberdeen
With Q&A

1:25–1:45 **Break**

1:45–3:15 **Session 2: Solar Climate Intervention**

Solar climate intervention encompasses techniques including stratospheric aerosol injection, marine cloud brightening, and cirrus cloud thinning. This session's panel will present the state of knowledge and readiness for these interventions, and engage in a robust discussion of the research, societal acceptance, and governance considerations surrounding this topic.

Welcome, Framing Remarks
Simone Tilmes, Session Chair

Keynote
Jim Haywood, University of Exeter

Panel
Ines Camilloni, University of Buenos Aires
Haruki Hirasawa, The University of Victoria
Karen Rosenlof, National Oceanic and Atmospheric Administration
Wake Smith, Harvard University
Daniele Visioni, Cornell University
With Q&A

3:15–3:30 **Break**

3:30–5:00 **Session 3: Land-based CDR and Reliable Sequestration**

Carbon dioxide removal (CDR) and sequestration are a set of negative emissions approaches falling under the umbrella of climate interventions. Land-based CDR and sequestration strategies including reforestation, forest management, soil carbon management, as well as bioenergy with carbon capture and storage and direct air capture, will be discussed in this session. This panel will discuss technological scalability and cost-effectiveness in this area, as well as societal considerations including siting and land-use.

Welcome, Framing Remarks
Phoebe Zarnetske, Session Chair

Keynote
Peter Lawrence, National Center for Atmospheric Research

Panel
Bruno Basso, Michigan State University
Sabine Fuss, Humboldt- Universität zu Berlin
Stephanie Roe, World Wildlife Fund
Gyami Shrestha, Lynker Corporation
With Q&A

5:00–5:15 **Day 1 Summary and Preview of Day 2**

Chris Field, Planning Committee member

5:15 **ADJOURN**

THURSDAY, JUNE 22, 2023 **Click Here for Q&A**

*All time is in Eastern Daylight Time (EDT)

11:00–11:05 **Welcome back & Recap of Day 1**

Jim Hurrell, Chair of Workshop Organizing Committee

11:05–12:35 **Session 4: Ocean-based CDR and Reliable Sequestration**

Ocean-based approaches for carbon dioxide removal and sequestration are a suite of climate interventions whose governance considerations, as well as approaches to technological development, are critical to consider. This session will address nutrient fertilization, artificial upwelling and downwelling, ocean alkalinity enhancement, in addition to electrochemical approaches, seaweed cultivation, and recovery strategies for ocean and coastal ecosystems.

Welcome, Framing Remarks
Joellen Russell, Session Chair

Keynote
Margaret Leinen, University of California San Diego

Panel
Phillip Boyd, University of Tasmania
Sarah Cooley, Ocean Conservancy
John Dunne, National Oceanic and Atmospheric Administration
Matthew Long, National Center for Atmospheric Research
Romany Webb, Columbia University
With Q&A

12:35–1:00 **Break**

1:00–2:30 **Session 5: The Role of the National Science Foundation**

This closing session will synthesize key insights and needs identified from the prior discussions, with an eye toward actionable steps for the National Science Foundation (NSF). This session will include a conversation on the best elements for convergent research proposals on climate intervention and what may be required as part of the review process to evaluate convergence in climate intervention research. Discussion pertaining to the design of NSF funding programs, including the roles for existing and new directorates, how NSF can coordinate with U.S. agencies and international efforts, as well as stay abreast of international debates and implications for US foreign relations, will also be held.

Welcome, Framing Remarks
Sonali McDermid, Session Chair

Keynote Speakers
Lynn Badia, Colorado State University
John Volckens, Colorado State University

Panel
James Arnott, Aspen Global Change Institute
Bill Easterling, Pennsylvania State University
Robert Kopp, Rutgers University
Michael Oppenheimer, Princeton University
Benjamin Sovacool, Boston University
With Q&A

2:30–2:45 **Synthesis Remarks**
Lili Xia, Planning Committee Member

2:45–3:00 **Next Steps and Future Work**
Brent Heard and Margo Corum, National Academies Staff

3:00 **MEETING ADJOURNS**

INVITED SPEAKER BIOGRAPHIES

James Arnott is the Executive Director of Aspen Global Change Institute (AGCI). Since 1989, AGCI has been an internationally recognized forum for interdisciplinary and solutions-oriented research. Dr. Arnott started his career with AGCI in 2008, finding inspiration from the late climate scientist Stephen H. Schneider's call for active engagement between science and society. Early encounters with water utilities and city governments seeking to use climate science to inform planning furthered Dr. Arnott's curiosity about what makes science actionable for decision-making. Since becoming AGCI's Executive Director in 2020, Dr. Arnott has led AGCI's suite of workshop, research, and technical assistance programs. James continues an active research agenda focused on the use of science to support climate and sustainability decision-making. He co-founded and co-leads the Science of Actionable Knowledge, a working group of social scientists studying the drivers of knowledge use. In 2017, he co-founded the Mountain West Climate Services Partnership. Dr. Arnott also represents AGCI in the Secretariat of the Crux Alliance, a consortia working across the largest emitting sectors and countries to reduce greenhouse gas emissions. In 2011, Dr. Arnott was awarded the McCloy Fellowship in Environmental Policy from the American Council on Germany. He is a visiting fellow at the University of Michigan. In 2019, he completed doctoral research at the University of Michigan on the influence of science funding on how research is used in practice.

Lynn Badia is Assistant Professor of English at Colorado State University. She is a research lead at CSU's Energy Institute, where she leads the education abroad program "Interdisciplinary Perspectives on Energy Transitions in Europe." In 2015, Dr. Badia was a Visiting Scholar at the University of Cambridge, as part of the Climate Histories Research Group at CRASSH Cambridge and Cambridge Interdisciplinary Research on the Environment. Dr. Badia's research in literature, theory, and film is focused on questions about scientific knowledge and the natural world from the nineteenth century to the present day, and she combines work in the fields of the history and philosophy of science, literary studies, and cultural studies. Her work is published by and forthcoming from a range interdisciplinary venues, such as American Quarterly, Cultural Studies, Resilience: A Journal of Environmental Humanities, Open Library of the Humanities, and Nineteenth-Century Contexts among others. She is currently completing her second monograph, Imagining Free Energy: Fantasies, Utopias, and Critiques of America, which introduces the concept of "free" or unlimited energy as a critical framework for understanding the conditions of American society since the beginning of the industrial era. Additionally, she co-wrote and edited the dual publication project Climate Realism: The Aesthetics of Weather, Climate, and Atmosphere. Before her graduate training, Dr. Badia was a documentary film producer in New York City. She was an Associate Producer for the six-hour PBS series, Broadway: The American Musical, which won two Emmy Awards including "Outstanding Nonfiction Series" in 2004. She received her PhD from the University of North Carolina, Chapel Hill.

Bruno Basso is John A. Hannah Distinguished Professor and MSU Foundation Professor of Earth and Environmental Sciences at Michigan State University. Dr. Basso is an agroecosystem scientist and a crop systems modeler with interest in long-term sustainability of agricultural systems, digital agriculture, circular bioeconomy. His research focuses on assessing and modeling spatial and temporal variability of crop yield, soil organic carbon, GHG emission, water, and nutrients fluxes across agricultural landscapes under current and future climates. He holds global patents on AI, remote sensing, and crop model systems to evaluate cropland productivity and environmental sustainability. Dr. Basso is a Fellow of the American Association for the Advancement of Science (AAAS); Soil Science Society of America (SSSA); American Society of Agronomy (ASA). He is the recipient of the 2021 Morgan Stanley Sustainability Solution Prize Collaborative; 2019 Outstanding Faculty Award at Michigan State University; 2016 Recipient of the Innovation of the Year Award from Michigan State. Dr. Basso serves as member of the Board of Agriculture and Natural Resources of the US National Academies of Sciences, Engineering and Medicine. He is a member of the Biological and Environmental Research Advisory Committee (BERAC), Department of Energy, Office of Science. He is ranked as top 2% scientist across all disciplines (PLOS one, 2021). He received his PhD from Michigan State University.

Philip Boyd is a Professor of marine biogeochemistry at the Institute for Marine and Antarctic Studies in Hobart, Australia. His interest in the field of marine climate intervention arose from coordinating and leading two open ocean mesoscale (1000 km2) iron fertilization studies to the Southern Ocean and Subarctic Pacific in the 2000's to better understand the links between iron supply and the global carbon cycle. The studies although not related to climate intervention revealed many insights into the challenges of such interventions. Dr. Boyd has been actively involved in this field since the mid 2000's ("Ranking Geoengineering Schemes" in Nature Geoscience 2008). He is currently a co-chair of the UN cross-agency GESAMP working group on marine climate interventions and co-led the GESAMP WG41 inaugural report in 2019. Within Australia he is a member of the virtual Climate Recovery Institute Climate Recovery Institute – Testing, assessing, and deploying technologies across Australia that remove CO2.

Holly Jean Buck is an Assistant Professor of Environment and Sustainability at the University at Buffalo. Previously, she was an Emmett Climate Engineering Fellow at the University of California Los Angeles. School of Law. Dr. Buck is a human geographer and environmental social scientist whose research focuses on public engagement with emerging climate technologies. Her research on carbon removal, solar geoengineering, and climate policy has appeared in journals like Nature Climate Change, Climatic Change, Nature Sustainability, Environmental Research Letters, and others, and she has also published two books related to climate intervention and decarbonization. Dr. Buck is a contributing author to the Intergovernmental Panel on Climate Change's AR6 Working Group III report chapter on cross-cutting issues, including governance of land-based mitigation, carbon removal, and food systems. She has also served on the National Academies committees to develop research agendas on ocean carbon removal and atmospheric methane removal. She earned her PhD in Development Sociology from Cornell University and a MS in Human Ecology from Lund University.

Ken Caldeira is a Climate Scientist at the Carnegie Institution for Science, where his job is “to make important scientific discoveries.” He also serves as a Professor (by courtesy) in the Stanford University Department of Earth System Science. Dr. Caldeira is a member of the committee producing the 2015 U.S. National Academy of Sciences report "Geoengineering Climate: Technical Evaluation and Discussion of Impacts". He is also a contributing author to the Intergovernmental Panel on Climate Change AR5 report Climate Change 2013: The Physical Science Basis. In 2010, Dr. Caldeira was a co-author of the 2010 US National Academy America's Climate Choices report and was elected Fellow of the American Geophysical Union. He participated in the UK Royal Society geoengineering panel in 2009 and ocean acidification panel in 2005. Dr. Caldeira was coordinating lead author of the oceans chapter for the 2005 INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE report on Carbon Capture and Storage. He received his BA from Rutgers College and both his MS and PhD in Atmospheric Sciences from New York University.

Ines Camilloni is an Associate Professor at the Department of Atmospheric and Oceanic Sciences of the University of Buenos Aires and Senior Researcher of the National Scientific and Technical Research Council at the Center for Atmosphere and Ocean Research (CIMA) in Argentina. Dr. Camilloni is also member of different committees and panels: World Commission on the Ethics of Scientific Knowledge and Technology of UNESCO, the Ethical Framework for Climate Intervention Advisory Board of the American Geophysical Union and the Scientific Advisory Committee of the Inter-American Institute for Global Change Research. Her research focuses on climate variability and change in South America, especially in cities and climate change and in the potential impacts of solar radiation modification. She has participated in and coordinated many national and international research projects related to these subjects. She has been lead author of the Intergovernmental Panel on Climate Change AR5-WG1 and SR15 reports and Review Editor of the the Intergovernmental Panel on Climate Change AR6-WG1. Dr. Camilloni was member of the Expert Panel to undertake a rapid review of the state of scientific research on Solar Radiation Modification recently published by UNEP.

Sarah Cooley is currently the Director of Climate Science at Ocean Conservancy. Previously, Dr. Cooley served as the Director of the Ocean Acidification program at Ocean Conservancy from 2014-2020 and was Research Associate III at Woods Hole Oceanographic Institution (WHOI) until 2014. Dr. Cooley’s expertise is in ocean carbon cycle science; ocean-based climate impacts, adaptations, and mitigation; science communication; and marine policy development and implementation. She is currently leading Ocean Conservancy’s advocacy for adoption of a code of conduct to guide the multidisciplinary ocean carbon dioxide removal research needed to make evidence-based decisions about these new approaches. This work draws from her experience at Ocean Conservancy advocating for passage of evidence-based ocean acidification legislation, appropriation of Federal funds to support ocean acidification research, and her experience at WHOI facilitating dialogue among the ocean acidification research community and Federal agency funders and scoping new activities. She is co-coordinating lead author of the “Oceans and Coastal Ecosystems and Their Services” chapter of the Intergovernmental Panel on Climate Change’s 6th Assessment Working Group II Report (2022), and co-lead author of the “Biogeochemical Effects of Rising Atmospheric Carbon Dioxide” chapter of the US’s 2nd State of the Carbon Cycle Report (2018 Dr. Cooley has published articles in Frontiers in Marine Science (2023) and Annual Review of Marine Science (2022) on research needs for ocean carbon dioxide removal, and served as an expert reviewer for the National Academies’ report “A Research Strategy for Ocean-Based Carbon Dioxide Removal and Sequestration” (2021). She received her BS in Chemistry from Haverford College and her PhD from University of Georgia’s School of Marine Science.

Michael Diamond is an Assistant Professor in the Department of Earth, Ocean, and Atmospheric Science at Florida State University. He was previously a CIRES Visiting Postdoctoral Fellow at the NOAA Chemical Sciences Laboratory and the University of Colorado Boulder. His research focuses on how the interactions between clouds and microscopic pollution particles influence Earth's climate. Dr. Diamond published the article "To Assess Marine Cloud Brightening's Technical Feasibility, We Need to Know What to Study—and When to Stop" in the Proceedings of the National Academies of Sciences, Engineering, and Medicine in 2022, identifying key priorities for marine cloud brightening research and their interdisciplinary linkages, and has presented at multiple geophysical conferences on the subject. He earned his BA in Earth and Environmental Sciences from Vanderbilt University and his MS and PhD in Atmospheric Sciences from the University of Washington Seattle.

John Dunne is a Supervisory Research Oceanographer leading the Biogeochemistry, Atmospheric Chemistry, and Ecosystems Division of NOAA's Geophysical Fluid Dynamics Laboratory in Princeton, NJ. He is an expert in ocean biogeochemistry, climate and earth system modeling with 30 years of experience developing instruments, collecting field observations, and performing analysis and modeling studies. Dr. Dunne co-led GFDL's Earth System Model Development Team adapting GFDL's models for coupled carbon-climate studies (ESM2M, ESM2G) participating in the fifth Coupled Model Inter-comparison Project (CMIP5) as well as the more recent climate (CM4) and coupled-carbon-chemistry-climate (ESM4) models participating in the current CMIP6. He has published over 150 peer-reviewed journal articles on topics relating to climate and earth system modeling, ocean ecosystems, and biogeochemistry. Ongoing foci include the merging of observational and modeling constraints on representation of physics and biogeochemistry in coastal, pelagic and benthic oceans, predictability of coupled physical-biological-ecological systems, Earth system interactions, and the role of heat, acidification, hypoxia and other stressors. Dr. Dunne recently served as a lead author on the Intergovernmental Panel on Climate Change Sixth Assessment Working Group I "Chapter 4: Future global climate: scenario-based projections and near-term information." He also serves on various international and national committees including the as co-Chair of the World Climate Research Programme's Coupled Model Intercomparison Project Panel, member of the US Climate Modeling Summit and External Advisory Board to the US GO-BGC program, and GFDL's science contact for Earth system modeling. Dr.Dunne is a member of the American Geophysical Union and has received the Department of Commerce Silver Medal in 2013 and 2022 and NOAA OAR Administrator Award in 2022. He earned his BS in Chemistry from the University of California San Diego, his MS and PhD from the University of Washington School of Oceanography.

William Easterling Dr. William E. Easterling, III resumed his appointment as Professor of Geography and Earth System Science at the Pennsylvania State University on June 1, 2021 after serving four years as Assistant Director of the National Science Foundation (NSF) in charge of the Geosciences Directorate. A Fellow of the American Association for the Advancement of Science (AAAS) and Fellow of the American Meteorological Society (AMS), prior to his service to NSF he was the dean of the College of Earth and Mineral Sciences 2007-2017 at Penn State. He received his bachelors, masters and PhD degrees in geography and climatology from the University of North Carolina at Chapel Hill. He is an internationally recognized expert on how climate change likely will affect the Earth's food supply and served as a convening lead author on the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report's Chapter on Food, Fibre, Forestry, and Fisheries. The lead authors of the IPCC Fourth Assessment Report were co-awarded the 2007 Nobel Peace Prize with former Vice President Al Gore. Easterling was a lead author on the 2015 USDA Report Climate Change, Global Food Security and the U.S. Food System, that received the 2016 Abraham Lincoln Honor Award for Increasing Global Food Security by the US Secretary of Agriculture.

Jane Flegal is a Social Scientist whose research has focused on the intersections of science, innovation, and social outcomes, particularly in the context of climate change. Dr. Flegal previously worked as a senior policy analyst on the Energy Team of the Bipartisan Policy Center, as a research consultant to the Organization for Economic Cooperation and Development and the California Council on Science and Technology. She has published on public participation and engagement in science and technology policy, equity concerns as they relate to climate technologies, and responsible research and innovation, including in Nature Climate Change and Annual Review of Environment and Resources. Currently, Dr. Flegal is the Market Development and Policy Lead at Stripe Climate and Frontier, a $1 billion advance market commitment to procure permanent carbon dioxide removal. Prior to joining Stripe, Dr. Flegal was the Senior Director for Industrial Emissions at the White House Office of Domestic Climate Policy. Previously, Dr. Flegal led the US Climate Programs at the Hewlett Foundation, as well as the Bernard and Anne Spitzer Charitable Trust. She is an affiliated faculty member at the School for the Future of Innovation in Society at Arizona State University. Dr. Flegal holds a PhD in Environmental Science, Policy, and Management from University of California Berkeley, and a BA in Environmental Studies and Politics from Mount Holyoke College.

Sabine Fuss is currently research group leader at the Mercator Research Institute on Global Commons and Climate Change (MCC) and holds a professorship on Sustainable Resource Management and Global Change at Humboldt University of Berlin. Previously, Dr.Fuss worked at the International Institute for Applied Systems Analysis (IIASA) in Laxenburg, Austria. Her expertise is in sustainable development, tropical rainforest conservation, and climate change mitigation, with a particular focus on Carbon Dioxide Removal from the atmosphere (CDR). Dr. Fuss was lead author for the Intergovernmental Panel on Climate Change's Special Report on Global Warming of 1.5°C and was appointed to the European Academy of Sciences in 2021. Dr. Fuss and colleagues published multiple articles on the assessment of CDR including the 2018 trilogy in Environmental Research Letters and are currently conducting several projects on CDR deployment at different scales. She received her PhD in Economics from Maastricht University.

Jim Haywood is a Professor of Atmospheric Science at the University of Exeter and a Research Fellow at the Met Office Hadley Centre. His expertise is in measurements and modelling of atmospheric aerosols and their associated aerosol-radiation-climate and aerosol-cloud-climate interactions. Dr. Haywood has been an author of three Intergovernmental Panel on Climate Change Assessments and was lead-author of the 2022 UN Scientific Assessment of Ozone Depletion for a chapter entitled Stratospheric Aerosol Injection and its Potential Effect on the Stratospheric Ozone Layer. He has led the UK's submissions to the Geoengineering Model Intercomparison (GeoMIP) for over a decade. Dr.Haywood has a keen interest in using observations of large scale naturally occurring aerosol events such as those from explosive volcanic eruptions, large-scale wildfires, and effusive volcanic eruptions to validate and improve global-scale models. He also led many in-situ measurement studies with dedicated atmospheric research aircraft examining the microphysical and radiative properties of aerosols. Dr. Haywood has published widely in the area of climate intervention using both stratospheric aerosol injection (SAI) and marine cloud brightening (MCB), and he leads groups at the University of Exeter and the Met Office Hadley Centre pursuing aerosol-climate research. He studied Physics at the undergraduate level before being awarded a PhD from the Department of Meteorology at Reading University, UK, which investigated the climate impacts of sulfate and black carbon aerosols from anthropogenic emissions.

Haruki Hirasawa is a Postdoctoral Researcher at the University of Victoria in Victoria, Canada. Dr. Hirasawa's expertise is in the field of climate model analysis, with a focus on understanding the climate impacts of anthropogenic aerosol forcing. In his research at the University of Victoria, he is helping lead the design, implementation, and analysis of earth system model simulations and artificial intelligence methods to assess the potential climate impacts of solar radiation management using marine cloud brightening and their uncertainties. Dr. Hirasawa recently submitted an article on the impact of marine cloud brightening on possible climate tipping elements. He currently serves as an early career representative for Atmospheric Research interest group the Canadian Meteorological and Oceanographic Society. He received a BS with honors in Physics and Applied Mathematics from the Memorial University of Newfoundland. Dr. Hirasawa received a PhD in Atmospheric Physics with a collaborative specialization in environmental studies from the University of Toronto in 2022, where he researched the impact of past sulphate aerosol pollution on West African climate.

Forrest M. Hoffman serves as group leader for the Computational Earth Sciences Group and as the Earth System Modeling (ESM) Theme Lead for the Climate Change Science Institute (CCSI) at Oak Ridge National Laboratory (ORNL). As Laboratory Research Manager for the U.S. Department of Energy (DOE)-funded Reducing Uncertainties in Biogeochemical Interactions through Synthesis and Computation (RUBISCO) Science Focus Area (SFA), he directs and conducts Earth system research focused on global biogeochemistry, terrestrial ecosystem science, and hydrological research, employing advanced computational methods and high performance computing resources. Dr. Hoffman also leads the DOE-funded Earth System Grid Federation 2-US (ESGF2-US) project, which archives and distributes model output data from Coupled Model Intercomparison Project (CMIP) simulations conducted by modeling centers all over the world. In addition, he develops and implements metrics for model evaluation, performs software engineering for Earth system models at scale on high performance computing architectures, and develops and applies methods for large scale data analytics and machine learning.

Robert Kopp is a Professor in the Department of Earth & Planetary Sciences and Co-Director of the University Office of Climate Action at Rutgers University. Dr. Kopp's research spans sea-level change, the interactions between physical climate change and the economy, and the use of climate risk information to inform decision-making. He directs the Megalopolitan Coastal Transformation Hub, a National Science Foundation-funded consortium that advances coastal climate adaptation and the scientific understanding of natural and human coastal climate dynamics. Dr. Kopp is also a director of the Climate Impact Lab, a collaboration of economists, data scientists, climate scientists, and policy experts that works to assess the economic risks of climate change. Dr. Kopp was a lead author of the Intergovernmental Panel on Climate Change's 2021 Sixth Assessment Report and of the U.S. Global Change Research Program's 2017 Fourth National Climate Assessment. He is a fellow of the American Geophysical Union (AGU) and the American Association for the Advancement of Science (AAAS), a recipient of AGU's James B. Macelwane medal, a past Leopold Leadership Fellow, and a past AAAS Science & Technology Policy Fellow. He is currently co-chair of National Academies' Roundtable on Macroeconomics and Climate-related Risks and Opportunities (2022-) and a member of the Board of Atmospheric Science and Climate (2017–2023). He received his PhD in Geobiology from the California Institute of Technology and his undergraduate degree in Geophysical Sciences from the University of Chicago.

Ben Kravitz is an Associate Professor in the Department of Earth and Atmospheric Science at Indian University. He is interested in using climate models to explore radiative forcing, climate response, and climate system feedbacks. Dr. Kravitz's main areas of focus are climate engineering using stratospheric sulfate aerosols, reduced order modeling of the climate system, high latitude climate teleconnections, and uncertainty quantification for wind energy. He is also interested in applying engineering techniques, such as control theory, system identification, and linear systems theory, to climate modeling. He earned his PhD and MS in Atmospheric Sciences from Rutgers University and MS in Mathematics from Purdue.

Peter Lawrence is a Project Scientist in the Terrestrial Sciences Section within the Climate and Global Dynamics Laboratory at National Center for Atmospheric Research. His research investigates how human and natural systems respond to the world's changing climate, and how human activities in turn impact back on the climate system. Since joining NCAR, Dr. Lawrence have become one of the agency's leading scientists on land use and land cover change, representing the agency in many international projects. The main focus of this research has been working on the World Meteorology Organization's (WMO) Coupled Model Intercomparison Projects (CMIP) which inform the United Nation's Intergovernmental Panel on Climate Change Assessment Reports. He received his PhD in Geobiology from the University of Queensland and BS from the Australian National University.

Margaret Leinen was appointed the eleventh Director of Scripps Institution of Oceanography at UC San Diego in July 2013. She also serves as UC San Diego's Vice Chancellor for Marine Sciences and Dean of the School of Marine Sciences. She is an award-winning oceanographer and distinguished national and international leader in ocean science, global climate, and environmental issues. Her research in paleo-oceanography and paleo-climatology focuses on ocean sediments and their relationship to global biogeochemical cycles and the history of Earth's ocean and climate. Dr. Leinen leads UC San Diego's ocean, earth, atmospheric and climate science research and education programs at Scripps Oceanography, the foremost environmental research institution addressing the pressing environmental problems facing our planet. Prior to joining Scripps, she served as Vice Provost for Marine and Environmental Initiatives and Executive Director of Harbor Branch Oceanographic Institute, a unit of Florida Atlantic University. At the University of Rhode Island, she was Vice Provost for Marine and Environmental Programs and Dean of the Graduate School of Oceanography. Dr. Leinen is also the founder and served as president of the Climate Response Fund. Dr. Leinen currently serves as co-chair of the Decade Advisory Board for UN Decade of Ocean Science for Sustainable Development and is a member of the distinguished Leadership Council of the Joint Ocean Commission Initiative. From 2016-2018 she served as a U.S. Science Envoy focusing on ocean science in Latin America, East Asia, and the Pacific. She has served as President of the American Geophysical Union, Chair of the Atmospheric and Hydrospheric Science Section of the American Academy for the Advancement of Science, and President of The Oceanography Society. She serves on the boards of the California Ocean Science Trust and Science Counts. She is the Vice Chair of the Research Board of the $500 million Gulf of Mexico Research Initiative. Dr. Leinen is a Fellow of the American Association for the Advancement of Science, the Geological Society of America, the American Geophysical Union and The Oceanography Society. She was elected an Honorary Member of the American Meteorological Society. She has been awarded Distinguished Alumni Awards from all three universities she attended as a student: University of Illinois, Oregon State University, and University of Rhode Island. In 2020, she was elected to the American Academy of Arts and Sciences. She received her PhD in Oceanography from the University of Rhode Island and her MS in Geological Oceanography from Oregon State University.

Matthew Long is a scientist in the Oceanography Section of the Climate & Global Dynamics Laboratory at the National Center for Atmospheric Research (NCAR) where he conducts research related to the carbon cycle, ocean biogeochemistry, and marine ecosystems in the context of climate variability and change. Dr. Long is also a co-founder and Executive Director of [C]Worthy, a non-profit research organization focused on supporting quantitative assessments of ocean carbon dioxide removal technologies. While in the United States Peace Corps, he taught high school physics as a volunteer in Tanzania. He also worked as a civil engineer developing river and sewer-network models to support management and guide municipal infrastructure investments and built automated instruments to measure ocean carbon variables and deployed these on research cruises in the Ross Sea, Antarctica and the Great Barrier Reef. At NCAR, Dr. Long leads the team developing ocean biogeochemistry and marine ecosystems components for the Community Earth System Model (CESM). He founded NCAR's Earth System Data Science initiative promoting collaborative software development and novel analytical frameworks and has served as co-Chair of the NCAR Scientist's Assembly. Dr. Long's research has addressed ocean deoxygenation, climate-driven variations in marine ecosystems, and the application of aircraft observations and models to constrain the global carbon cycle. At [C]Worthy, Dr. Long is directing a team of scientists and engineers to develop frameworks for quantifying ocean carbon dioxide removal, building research infrastructure necessary to provide robust monitoring and verification of these technologies. He earned his master's and bachelor's degrees in civil and environmental Engineering from Tufts University and a PhD in Oceanography from Stanford University.

Phil Macnaghten is a Professor of Technology and International Development at the Knowledge, Technology and Innovation (KTI) group at the Wageningen University (NL). His research background is in science and technology studies (STS) and sociology. His current research focuses on responsible innovation, gene editing and the governance of science. Dr. Macnaghten is a fellow of the Academy of Social Sciences (FAcSS), on the editorial board of the Journal of Responsible Innovation and an editor of the journal Plants, People, Planet. He chaired the UK EPSRC Stratospheric Particle Injection for Climate Engineering (SPICE) Stagegate Panel (2011–2012), an early experiment in governance that contributed to the halting of the UK's first field trial of climate engineering. Dr. Macnaghten earned his PhD from Exeter (UK) and he has held appointments at Lancaster (UK), Durham (UK) and Campinas (Br) before joining Wageningen in 2015.

Juan Moreno-Cruz is an Associate Professor at the School of Environment, Enterprise and Development and holds the title of Canada Research Chair in Energy Transitions at the University of Waterloo. He is also the Associate Director of the Waterloo Climate, which promotes the climate research agenda on campus. Dr. Moreno-Cruz is an adviser and member of the mitigation board for the Canadian Climate Institute. He is also an advisor for New Energy Options and an Associate at Harvard's Solar Geoengineering Research Program. His research primarily explores the nexus of energy systems, technological change, and climate policy. He is renowned for his influential studies on how solar and carbon geoengineering technologies impact climate policy. Dr. Moreno-Cruz was part of the National Academies of Sciences, Engineering, and Medicine committee on Solar Geoengineering Research and Governance Report. He earned his PhD in Economics from the University of Calgary, and both a BA and MS in Electrical Engineering from the Universidad de Los Andes.

Simon Nicholson is Associate Professor of International Relations. His work focuses on global environmental governance, global food politics, and the politics of emerging technologies, including climate engineering and carbon removal technologies. Dr. Nicholson is co-founder of the Forum for Climate Engineering Assessment and the Institute for Carbon Removal Law and Policy, two scholarly initiatives of the School of International Service. He received his PhD in International Relations from American University.

Michael Oppenheimer is the Albert G. Milbank Professor of Geosciences and International Affairs at Princeton University and Director of the Center for Policy Research on Energy and the Environment. Dr. Oppenheimer has authored the Intergovernmental Panel on Climate Change reports, which won the Nobel Peace Prize in 2007, since its First Assessment Report (1990). He is a science advisor to the Environmental Defense Fund and member of several boards of directors including the Board of the Trust for Governors Island (NYC), the future site of a major climate science research and education center focused on solutions to this problem. Dr. Oppenheimer is a Heinz Award winner and a Fellow of the American Association for the Advancement of Science. Oppenheimer is the Co-Editor-in-Chief of the journal Climatic Change. Much of his work has centered on defining the concept of "dangerous" climate change, a key aspect of the UN Framework Convention on Climate Change and the Paris Agreement.

Stephanie Roe is the Global Climate Lead Scientist at World Wildlife Fund (WWF). She is also a Lead Author of the Intergovernmental Panel on Climate Change Sixth Assessment Report and is a member of the Science-Based Targets Initiative (SBTi) Technical Council. Previously, Dr. Roe was at Climate Focus where she led research on climate and sustainable land-use science and developed related strategies and projects with governments, NGOs, private sector and local communities in over 20 countries. She also worked with the United Nations to address deforestation in Indonesia and advised Fortune 500 companies and cities on climate strategies at The Climate Group. Dr. Roe's expertise focuses on land-based climate mitigation, 1.5ºC sectoral pathways, biodiversity and climate interactions, and the response of terrestrial ecosystems to climate change. Dr. Roe holds a PhD in Environmental Sciences from the University of Virginia, a MEM in Ecosystem Science from Duke University, and a BA from San Diego State University.

Katherine Romanak is currently a Research Scientist at the University of Texas at Austin's Bureau of Economic Geology. She is an environmental geochemist who has been researching the safety and environmental impacts of CO2 geologic storage for over 17 years. Dr. Romanak has developed monitoring programs and protocols for more than six actively-injecting large-scale CO2 storage projects dating back to 2007. She pioneered a process-based soil gas approach which has created a paradigm shift in near-surface monitoring. She has championed the concept of leakage "attribution" as a critical part of monitoring in the near-surface. Dr. Romanak was the independent technical lead to assess the first-ever claim of leakage by a farmer living near a CO2 injection site. Using attribution techniques, she and her team determined that no leakage had occurred at the Kerr Farm, and the experience outlined the importance of having protocols for responding to stakeholder concerns in place before a project begins. Dr. Romanak regularly inputs technical information on CCS into global regulations at the UNFCCC COPs and other global platforms. She effectively conveys environmental safety of geological CO2 storage to a wide audience of stakeholders.

Karen H. Rosenlof is a Senior Scientist with the NOAA Chemical Sciences Laboratory. Prior to joining NOAA, she held positions as an operational meteorologist (NWS) and a research assistant (LASP, University of Colorado). Dr. Rosenlof currently leads the Chemistry and Climate Processes Program within the Chemical Sciences Laboratory. She has considerable expertise in the interpretation of stratospheric water vapor and ozone data from in situ sources and satellite. Dr. Rosenlof research uses constituent and temperature measurements to understand dynamical processes in the stratosphere, incorporating data analysis with a spectrum of models of varying complexity. Her work has focused on understanding trends and variability of constituents and transport in the stratosphere. Dr. Rosenlof has worked on over 25 aircraft experiments (with NASA, NOAA and NCAR) and several climate and ozone assessments, was a member of 4 satellite science teams, and served as chair of the American Meteorological Society's (AMS) Middle Atmosphere Committee. She currently serves as a co-chair for Stratosphere-troposphere Processes and their Role in Climate (SPARC, a core project of the World Climate Research Program). Dr. Rosenlof received the AMS Clarence Leroy Meisinger Award in 2000, "for outstanding observational and theoretical analysis of the stratospheric circulation and trace constituent transport" and the American Geophysical Union's (AGU) Yoram J. Kaufman Unselfish Cooperation in Research Award in 2016. She was elected as an American Meteorological Society fellow in 2014 and was a member of teams that received NOAA Bronze awards in 2007 and 2013. Dr. Rosenlof earned her undergraduate degree from the University of California at Davis, her MS from the Colorado State University and PhD from University of Washington.

Gyami Shrestha is a Program Director at Lynker Corporation for its carbon, GHG, climate and weather portfolio. Dr. Shrestha spearheaded the U.S. Carbon Cycle Science Program Office for 11 years as Director, catalyzing interagency and community science products and collaborations. She shepherded the development of the Interagency Carbon Dioxide Removal Research Coordination (I-CDR-C) work group, which informed recent U.S. government investments and strategies for carbon removal research, as described in her Dec 2022 paper published in Issues in Science and Technology. With over 20 years of multidisciplinary experience in academia, non-profit and private sectors, she published over 100 influential publications (such as the State of the Carbon Cycle Report), presentations, projects and public engagement opportunities for and with U.S. and international partners and rights holders. Dr. Shrestha was awarded the UCAR Special Recognition Award for Extraordinary Work of Outstanding Quality and Commitment and has provided expertise to several scientific panels and advisory committees such as the Community Climate Interventions Strategy (CCIS) Steering Committee and the World Climate Research Program (WCRP) Climate Interventions Task Team. Dr. Shrestha earned a PhD in Environmental Systems, focused on black carbon, biochar and forest fire management from the University of California Merced, followed by executive training certificates in Non-Profit Executive Management, Sustainability Leadership and Senior Executive Development from Georgetown University, Harvard University and the Asian American Government Executives Network respectively.

Pete Smith is a Professor of Soils and Global Change at the Institute of Biological and Environmental Sciences at the University of Aberdeen (Scotland, UK) and Science Director of the Scottish Climate Change Centre of Expertise (ClimateXChange). Dr. Smith's interests include climate change mitigation, soils, agriculture, food systems, greenhouse gas removal options, ecosystem services modelling and nature-based solutions. He has received awards from the Royal Society, the British Ecological Society, and the European Geosciences Union. Dr. Smith is a Fellow of the Royal Society of Biology, a Fellow of the Institute of Soil Scientists, a Fellow of the Royal Society of Edinburgh, a Foreign Fellow of the Indian National Science Academy, a Fellow of the European Science Academy, and a Fellow of the Royal Society (London). He earned his PhD from University of Reading.

Wake Smith is a Lecturer in the Yale School of Environment, where he teaches a graduate level course on climate engineering. Mr. Smith is also a Research Fellow at the Harvard Kennedy School. His Yale course material was published in book form in March 2022 by the Cambridge University Press under the title Pandora's Toolbox: The Hopes and Hazards of Climate Intervention. Mr. Smith has published papers on the aeronautics, costs, and governance of solar geoengineering and developed preliminary designs for high altitude research aircraft. Mr. Smith finished his business career in private equity with New York based New State Capital, and previously served as Chairman and President of Pemco World Air Services; Chief Operating Officer of Atlas Air Worldwide Holdings; and President of the flight training division of The Boeing Company. He earned his BA in History from Yale and an MBA from Harvard.

Benjamin K. Sovacool is a Professor of Earth and Environment at Boston, where he is the Founding Director of the Institute for Global Sustainability, as well as Professor of Energy Policy at the Science Policy Research Unit (SPRU) at the University of Sussex Business School in the United Kingdom. He is also University Distinguished Professor of Business & Social Sciences at Aarhus University in Denmark. Dr. Sovacool works as a researcher and consultant on issues pertaining to energy policy, energy justice, energy security, climate change mitigation, and climate change adaptation. More specifically, his research focuses on renewable energy and energy efficiency, the politics of large-scale energy infrastructure, the ethics and morality of energy decisions, designing public policy to improve energy security and access to electricity, and building adaptive capacity to the consequences of climate change. Dr. Sovacool's research has been endorsed by U.S. President Bill Clinton, the Prime Minister of Norway Gro Harlem Brundtland, and the late Nobel Laureate Elinor Ostrom, among others. He was a Lead author of the Intergovernmental Panel on Climate Change's Sixth Assessment Report (AR6), published in 2022, and he serves on the Board on Environmental Change and Society for the National Academies of Sciences, Engineering, and Medicine in the United States. Dr. Sovacool has played a leadership role in winning collaborative research grants worth more than $35 million in directly managed funds on proposals worth more than $245 million, including those from the U.S. Department of Energy, U.S. National Science Foundation, MacArthur Foundation, Rockefeller Foundation, Energy Technology Development and Demonstration Program of Denmark, the Danish Council for Independent Research, the European Commission, and the European Research Council. In the United Kingdom, he has served as a Principal Investigator on projects funded by the Economic and Social Research Council, Natural Environment Research Council, and the Engineering and Physical Sciences Research Council. Dr. Sovacool is the recipient of multiple national and international awards and honors, including the "Distinguished Graduate Alumni Achievement Award" from his Alma Mater Virginia Tech, the 2019 USERN Prize for his work on "Social Justice in an Era of Climate Change and Energy Scarcity," and the "Dedication to Justice Award" given by the American Bar Association. With much coverage of his work in the international news media, he is one of the most highly cited global researchers on issues bearing on controversies in energy and climate policy.

Christopher Trisos directs the Climate Risk Lab at the University of Cape Town. His research focus is on climate change risks to people and ecosystems, including from solar radiation modification, and how to manage risk across interconnected social and environmental systems. Dr Trisos was a Coordinating Lead Author on the Intergovernmental Panel on Climate Change's 6th Assessment Report, responsible for Chapter 9 of Working Group II on Climate Change Impacts, Adaptation and Vulnerability in Africa. He was also a Core Writing Team member of the Intergovernmental Panel on Climate Change Synthesis Report. Dr Trisos has advised on climate change for several organizations, including the World Bank and United Nations Environment Program.

Romany Webb is Deputy Director of the Sabin Center for Climate Change Law, an Associate Research Scholar at Columbia Law School, and an Adjunct Assistant Professor of Climate at Columbia Climate School. Her research focuses on two primary areas: (1) energy and (2) negative emissions technologies. Romany's energy-related research explores how legal and policy tools can be used to minimize the climate impacts of energy development as well the impacts of climate change on energy infrastructure. Romany also researches legal issues associated with the development and deployment of negative emissions technologies on land and in the ocean. From 2020 through 2022, she served on the National Academy of Sciences, Engineering, and Medicine Committee on Ocean Carbon Dioxide Removal and Sequestration. She now co-chairs the Climate Change, Sustainable Development, and Ecosystems Committee of the American Bar Association's Section of Environment, Energy, and Resources and serves on a number of other boards and advisory councils. Prior to joining the Sabin Center, she worked at the University of California Berkeley Energy and Climate Institute, researching executive authority to combat climate change. Romany also completed a fellowship with the Kay Bailey Hutchison Center for Energy, Law, and Business at the University of Texas at Austin, where she researched energy policy. The fellowship followed several years working in private practice in Sydney, Australia. She received an LL.M., with a certificate of specialization in environmental law, from the University of California, Berkeley. She also holds an LL.B., awarded with first class honors, from the University of New South Wales (Australia).

Daniele Visioni is an Assistant Professor in the department of Earth and Atmospheric Sciences at Cornell University. Dr. Visioni is the co-chair of the Geoengineering Model Intercomparison Project (GeoMIP), a World Meteorological Organization (WMO) endorsed model intercomparison with the aim of devising and carrying out climate model experiments of different Climate Intervention strategies across a wide range of climate models around the world. His expertise is in stratospheric aerosols and their interaction with stratospheric chemistry, dynamics, and with surface climate. Dr. Visioni was a co-author of the latest WMO Ozone Assessment Report 2022, in a new chapter related to the possible interaction between Stratospheric Aerosol Injections and stratospheric ozone. He's a research collaborator for the Degrees Modeling Fund (DMF), which aims to build the capacity of developing countries to evaluate Climate Intervention strategies and has active collaborations with a wide range of experts trying to understand the climatic, ethical, societal, and ecological impacts of Climate Intervention. He received his PhD from the University of L'Aquila, Italy in Atmospheric Physics and Chemistry.

John Volckens is a Professor of Mechanical Engineering and the Director of the Center for Energy Development and Health at Colorado State University (CSU). He holds affiliate appointments in Environmental Health, Biomedical Engineering, the Colorado School of Public Health, and the CSU Energy Institute. Dr. Volckens research interests involve air quality, low-cost sensors, exposure science, and air pollution-related disease. He is a founding member of the CSU Partnership for Air Quality, Climate, and Health – an organization that seeks to develop practical, science-vetted solutions to intertwined problems of air quality, climate, and health that we face as a society. Dr. Volckens was a Postdoctoral Fellow at the U.S. EPA's National Exposure Research Laboratory in Research Triangle Park, NC. At CSU, he has pioneered the development of several new aerosol measurement technologies, which have been deployed for public health research in over 40 different countries and as far away as the International Space Station. He is a co-founder of Access Sensor Technologies, a company started through his research collaborations at Colorado State University. Dr. Volckens is the recipient of 'Best Paper' awards from the American Industrial Hygiene Association (1999, 2017, 2021) and the Journal of Indoor Air (2013). He was a 2018 finalist for the NASA Earth, Space, Air Prize. Dr. Volckens received a BS in Civil Engineering from the University of Vermont and MS, PhD degrees in Environmental Engineering from the Gillings School of Public Health at the University of North Carolina at Chapel Hill.

NATIONAL ACADEMIES *Sciences Engineering Medicine*

PREVENTING DISCRIMINATION, HARASSMENT, AND BULLYING:
POLICY FOR PARTICIPANTS IN NASEM ACTIVITIES

The National Academies of Sciences, Engineering, and Medicine (NASEM) are committed to the principles of diversity, inclusion, integrity, civility, and respect in all of our activities. We look to you to be a partner in this commitment by helping us to maintain a professional and cordial environment. **All forms of discrimination, harassment, and bullying are prohibited in any NASEM activity.** This policy applies to all participants in all settings and locations in which NASEM work and activities are conducted, including committee meetings, workshops, conferences, and other work and social functions where employees, volunteers, sponsors, vendors, or guests are present.

Discrimination is prejudicial treatment of individuals or groups of people based on their race, ethnicity, color, national origin, sex, sexual orientation, gender identity, age, religion, disability, veteran status, or any other characteristic protected by applicable laws.

Sexual harassment is unwelcome sexual advances, requests for sexual favors, and other verbal or physical conduct of a sexual nature that creates an intimidating, hostile, or offensive environment.

Other types of harassment include any verbal or physical conduct directed at individuals or groups of people because of their race, ethnicity, color, national origin, sex, sexual orientation, gender identity, age, religion, disability, veteran status, or any other characteristic protected by applicable laws, that creates an intimidating, hostile, or offensive environment.

Bullying is unwelcome, aggressive behavior involving the use of influence, threat, intimidation, or coercion to dominate others in the professional environment.

REPORTING AND RESOLUTION

Any violation of this policy should be reported. If you experience or witness discrimination, harassment, or bullying, you are encouraged to make your unease or disapproval known to the individual at the time the incident occurs, if you are comfortable doing so. You are also urged to report any incident by:

- Filing a complaint with the Office of Human Resources at 202-334-3400 or hrservicecenter@nas.edu, or
- Reporting the incident to an employee involved in the activity in which the member or volunteer is participating, who will then file a complaint with the Office of Human Resources.

Complaints should be filed as soon as possible after an incident. To ensure the prompt and thorough investigation of the complaint, the complainant should provide as much information as is possible, such as names, dates, locations, and steps taken. The Office of Human Resources will investigate the alleged violation in consultation with the Office of the General Counsel.

If an investigation results in a finding that an individual has committed a violation, NASEM will take the actions necessary to protect those involved in its activities from any future discrimination, harassment, or bullying, including in appropriate circumstances **the removal of an individual from current NASEM activities and a ban on participation in future activities**.

CONFIDENTIALITY

Information contained in a complaint is kept confidential, and information is revealed only on a need-to-know basis. NASEM will not retaliate or tolerate retaliation against anyone who makes a good faith report of discrimination, harassment, or bullying.

Updated December 2, 2021

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Background Information

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Climate Intervention in an Earth Systems Science Framework: A Workshop

Statement of Task:

The National Academies will convene a workshop to consider the application of climate interventions from an Earth Systems Science approach. The workshop will address aspects of climate intervention research that would benefit from an Earth Systems Science approach, including potential unintended consequences, and interactions among and comparisons between proposed climate intervention strategies and other climate responses. The committee will evaluate the spectrum of interventions from the prior National Academies' reports focusing on multiple Earth systems (e.g., agricultural, coastal systems) to focus their discussions, with a goal of identifying crosscutting needs and opportunities for NSF to address those needs. The discussion will focus on scientific gaps, unintended consequences on Earth systems, and sustainability, governance, and ethical concerns.

The presentations and discussions at the workshop will be published as a workshop proceedings-in-brief prepared by a rapporteur in accordance with institutional guidelines.

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In September 2021, the National Academies released the consensus study, Next Generation Earth Systems Science at the National Science Foundation. The report called for an Earth systems science initiative that emphasizes research on complex interconnections and feedbacks between natural and social processes. It noted that such an initiative will require NSF to place an increased emphasis on research inspired by real-world problems while maintaining their strong legacy of curiosity driven research across many disciplines – as well as enhance the participation of social, engineering, and data scientists, and strengthen efforts to include diverse perspectives in research. This workshop is a part of a series of workshops on topics from the consensus study. Additional reports generated by NASEM for background information are listed below.

Climate Intervention: Carbon Dioxide Removal and Reliable Sequestration (2015)

Climate Intervention: Reflecting Sunlight to Cool Earth (2015)

Negative Emissions Technologies and Reliable Sequestration: A Research Agenda (2019)

Reflecting Sunlight: Recommendations for Solar Geoengineering Research and Research Governance (2021)

A Research Strategy for Ocean-based Carbon Dioxide Removal and Sequestration (2021)

NATIONAL ACADEMIES Sciences Engineering Medicine

Climate Intervention in an Earth Systems Science Framework: A Workshop System

COMMITTEE ROSTER

James Hurrell (Chair)
Colorado State University

Christopher Field (NAS)
Stanford University

Sonali Shukla McDermid
New York University

Manjana Milkoreit
University of Oslo

Joellen Louise Russell
University of Arizona

Simone Tilmes
National Center for Atmospheric Research

Lili Xia
Rutgers University

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NATIONAL ACADEMIES Sciences Engineering Medicine

COMMITTEE BIOS

CHAIR

Dr. James (Jim) W. Hurrell is the Scott Presidential Chair of Environmental Science and Engineering at Colorado State University. Previously, Dr. Hurrell served as the Director of the National Center for Atmospheric Research (NCAR), where he was also a Senior Scientist in the Climate and Global Dynamics Laboratory (CGD). He also served as Chief Scientist of the Community Earth System Model, and Director of CGD. Dr. Hurrell's research has centered on empirical and modeling studies and diagnostic analyses to better understand climate, climate variability, climate predictability. He has also researched the possible risks and benefits of climate intervention strategies. Dr. Hurrell has received numerous professional awards, including the Warren Washington Research and Leadership Medal from the American Meteorological Society (AMS). He is a Fellow of AMS, the Royal Meteorological Society, and the American Geophysical Union. Dr. Hurrell received a Ph.D. in Atmospheric Science from Purdue University (1990). He also served on several National Academy committees, including Reflecting Sunlight: Recommendations for Solar Geoengineering Research and Research Governance (2021).

MEMBERS

Dr. Christopher Field is the Perry L. McCarty Director of the Stanford Woods Institute for the Environment and Melvin and Joan Lane Professor for Interdisciplinary Environmental Studies. Dr. Field's research focuses on climate change, especially solutions that improve lives now, decrease the amount of future warming, and support vibrant economies. Recent projects emphasize decreasing risks from coastal flooding and wildfires. Dr. Field was the founding director of the Carnegie Institution's Department of Global Ecology, a position he held from 2002 to 2016. He was co-chair of Working Group II of the Intergovernmental Panel on Climate Change from 2008-2015, where he led the effort on the IPCC Special Report on "Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation" (2012) and the Working Group II contribution to the IPCC Fifth Assessment Report (2014) on Impacts, Adaptation, and Vulnerability. Dr. Field's widely cited work has earned many recognitions, including election to the National Academy of Sciences, the American Academy of Arts and Sciences, and the American Philosophical Society, as well as the Heinz Award, the Max Planck Research Award, the BBVA Frontiers of Knowledge Award, the Roger Revelle Medal, and the Japan Prize.

Dr. Sonali Shukla McDermid is an Associate Professor and climate scientist in the Dept. of Environmental Studies at New York University (NYU), and currently serves as Editor-in-Chief for the American Meteorological Society journal Earth Interactions. Dr. McDermid's research focuses on both climate change impacts on agriculture and food security, and the impacts of agricultural land management on the environment. She is a Climate Co-Lead for the Agricultural Intercomparison and Improvement Project's Regional Integrated Assessments (www.agmip.org), evaluating climate change impacts on food security across South Asia and Sub-Saharan Africa. She is also affiliated with the NASA

Goddard Institute for Space Studies, where she contributes to development of the land surface model to improve representations of agriculture and its feedbacks to the climate system. Furthermore, she is a recent Andrew Carnegie Fellow (2021) and Fulbright-Kalam Fellow awardee (2020), which support her research investigating pathways for combined climate mitigation and adaptation in rice-based agricultural systems. She holds a B.A. in Physics from NYU and a Ph.D. from the Department of Earth and Environmental Sciences at Columbia University, focusing on Atmospheric Science and Climatology. Prior to NYU, she was a NASA Postdoctoral Fellow at the Goddard Institute for Space Studies.

Dr. Manjana Milkoreit is a Postdoctoral Researcher at the University of Oslo's Department of Sociology and Human Geography. Prior to joining the University of Oslo, Dr. Milkoreit was an Assistant Professor at the Department of Political Science at Purdue University. Her research integrates global environmental governance and cognitive theory to study actor motivations, agency, and institutional effectiveness related to climate change. Dr. Milkoreit is also interested in challenges at the science-policy-society interface, including the use of scientific knowledge in environmental decision-making and the role of ideologies in advancing or preventing effective responses to climate change. Currently, Dr. Miloreit's research focuses on collective future thinking (imagination) in climate change governance and the challenges associated with climate and social tipping points. Dr. Milkoreit holds a Ph.D. in Global Governance from the University of Waterloo (Canada) and a Master's in Public Policy from the Harvard Kennedy School.

Dr. Milkoreit served as a panelist for the Norwegian Institute of Foreign Affairs (NUPI) seminar series on climate policy entitled "Is delay the new denial in climate policy?" and spoke on climate dioxide removal as a tool in climate policy.

Dr. Joellen Russell is a Distinguished Professor at the University of Arizona (UA) and is the Thomas R. Brown Distinguished Chair in Integrative Science. Dr. Russell is an oceanographer and climate scientist who uses robot floats, supercomputers and satellites to observe and predict the ocean's role in climate and the carbon cycle. Dr. Russell is the lead for the modeling theme of the Southern Ocean Carbon and Climate Observations and Modeling project (SOCCOM) including its Southern Ocean Model Intercomparison Project (SOMIP). She currently serves as Co-Chair of the NOAA Science Advisory Board's Climate Working Group and on the National Center for Atmospheric Research's Community Earth System Model Advisory Board. Before joining UA, Dr. Russell was a Research Scientist at Princeton University and the National Ocean and Atmospheric Administration's Geophysical Fluid Dynamics Laboratory (NOAA/GFDL). Dr. Russell received her A.B. in Environmental Geoscience from Harvard and her PhD in Oceanography from Scripps Institution of Oceanography, University of California, San Diego.

Dr. Simone Tilmes is a Project Scientist III at National Center for Atmospheric Research (NCAR) and the co-chair of the Community Earth System Model (CESM) chemistry-climate working group. Dr. Tilmes scientific interests cover the understanding and evaluation of chemical, aerosol and dynamical processes in chemistry-climate models. She has investigated past, present and future evolution of the ozone hole in both hemispheres based on models and observations. Currently, Dr. Tilmes research focuses on troposphere chemistry, aerosols, air quality, long-range transport of pollutants, and of tropospheric

ozone. She further studies the impact of climate interventions in particular stratospheric aerosol intervention, on the Earth's climate system, the hydrological cycle, and the impact of solar radiation management on dynamics and chemistry in both troposphere and stratosphere. Dr. Tilmes serves on several panels, including the Geoengineering Modeling Intercomparison Project Steering Committee and the Geoengineering Modeling Research Consortium Steering Committee, and will be the next co-chair of the Gordon Research Conference for Climate Engineering in 2024. She is further one of the PIs of the Community Climate Intervention Strategies Program at NCAR and served as a chapter lead author on the recent WMO2022 ozone assessment report with the title: "Stratospheric aerosol injection and its potential effects on the stratospheric ozone layer". Dr. Tilmes holds a M.S. in Geophysics from the University of Cologne and a Ph.D. in Geophysics and Geography from Johann Wolfgang Goethe University.

Dr. Lili Xia is an Assistant Research Professor in the Department of Environmental Sciences at Rutgers University. She is co-director of Rutgers Impact Studies of Climate Intervention (RISCI). Currently, Dr. Xia is serving as a research collaborator in the Developing Country Impact Modelling Analysis for Solar Radiation Management (DECIMALS) project to help teams from the Philippines, Jamaica, West Africa, and South Africa since 2017. Dr. Xia is also a steering committee member of the Geoengineering Modeling Research Consortium from 2019 to 2022. She has been working on climate change impact on agriculture, ecosystem, and air pollutants. Dr. Xia research focuses on two climate scenarios, stratospheric aerosol intervention and nuclear war. In 2022, Dr. Xia received the Global Peace and Health Award from the International Physicians for Prevention of Nuclear War and the Boston Chapter of Physicians for Social Responsibility. In 2022, she served in a NOAA review panel for the Earth's Radiation Budget Program "Atmospheric aerosols and their potential roles in solar climate intervention methods". Dr. Xia received her Ph.D. in Atmospheric Sciences Graduate Program at Rutgers University–New Brunswick.

Dr. Phoebe Lehmann Zarnetske is Associate Professor of spatial and community ecology in the Department of Integrative Biology at Michigan State University (MSU) and is Director of the Institute for Biodiversity, Ecology, Evolution, and Macrosystems (IBEEM). Dr. Zarnetske is a co-leads the NSF-funded Climate Intervention Biology Working Group, bringing together experts in climate science and ecology to research the potential ecological impacts from solar radiation modification. Her research on climate change ecology has elucidated important roles of biotic interactions among species, and how these interactions can exacerbate the impacts of climate change on biodiversity. Dr. Zarnetske's research integrates insights from climate change experiments with macrosystems science and modeling of big data in ecology across spatial scales. She received the Early Career Research Award (MSU College of Natural Science), is lead PI of NSF Macrosystems NEON and NASA grants, and is a Co-PI of the Kellogg Biological Station Long-Term Ecological Research (LTER) site. Dr. Zarnetske was a Yale Climate and Energy Institute Postdoctoral Fellow in the Yale School of the Environment, a NSF IGERT Fellow during her Ph.D. in Integrative Biology, Ecosystem Informatics, Statistics at Oregon State University, and received her M.S. in Ecology from Utah State University and B.A. in Biology and Environmental Science from Colby College.