Image: NOAA NWS   Image: NASA   Image: EPA

WORKSHOP ON

EARTH SYSTEM PREDICTABILITY RESEARCH & DEVELOPMENT

June 4-5, 2020

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Workshop on Earth System Predictability R&D Agenda
June 4-5, 2020

Image: NOAA NWS   Image: NASA   Image: EPA

Opportunity for additional input and discussion BEFORE and AFTER the meeting
In the days leading up to workshop, please join our Earth System Predictability R&D Slack Workspace! Within the workspace, we have created a channel for each of the 6 workshop sessions. Please use this space to share information on the topic (including slides, papers, or other resources), and to post questions or comments before or after the workshop. We will use this information to spark discussion during the workshop and allow for conversation after the workshop. Questions regarding the Slack channel? Please email Rob Greenway, rgreenway@nas.edu

To join the Virtual Workshop:
Please use the link embedded in the project website here. All questions and comments will be submitted to the panel using a chat tool, called Pubble, which will be integrated with the webcast in real-time. If you experience difficulty joining the webcast, please email: support@sparkstreetdigital.com

Summary:
Understanding to what degree different features of the Earth system are predictable across its physical and biogeochemical components – from individual thunderstorms, to regional or continental-scale droughts and floods, to fishery and crop yields – has great practical value to society. Past research into Earth system predictability has led to profound insights into the Earth system and has facilitated improved predictions. However, to accelerate progress in providing practicable predictions across a broader set of phenomena, it is important to know predictability limits and opportunities that are crucial for optimizing federal investments. In the Memorandum, "Fiscal Year 2021 Administration Research and Development Budget Priorities", Departments and Agencies are directed to prioritize R&D in the area of Earth system predictability, with an

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awareness of its importance to society. This workshop is designed to promote a discussion of relevant issues and solicit feedback on the direction that the Federal government should take in this area. While the prediction problem itself is seamless, discussions will emphasize Earth system predictability from intraseasonal through interannual timescales.

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June 4, 2020

*All time is Eastern Daylight Time (EDT)

11:00 AM   **Welcome and Purpose of the Workshop**
Jim Hurrell, Chair of ESP R&D Workshop Organizing Committee (5 min)
Kelvin Droegemeier, Office of Science and Technology Policy (10 min)

11:15 AM   **Purpose-driven Practicable Predictability**

Addressing "practicable predictability" requires understanding the information needs of decision makers and incorporating that understanding into Earth system predictability research. This session will focus on the demand for predictions, explore the barriers to expanding their utility, and emphasize the importance of understanding predictability for the development of co-designed prediction systems.

Chair:	Brad Colman, The Climate Corporation
Plenary Speaker:	Sarah Jones, Deutscher Wetterdienst
Panelists:	Nathan Mantua, NOAA
	Olga Wilhelmi, NCAR
	Roger Pulwarty, NOAA
	Andrew Robertson, IRI, Columbia University

12:45 PM   Break

1:15 PM   **Theoretical Limits on Earth System Predictability**

This session will focus on the theoretical foundations of Earth system predictability. Our current understanding of predictability limits is based on imperfect models and incomplete understanding and representation of critical processes, such as those linking the atmosphere to more slowly-evolving components of the Earth system. How can targeted research improve our understanding of Earth system predictability limits?

Chair:	Jim Hurrell, Colorado State University
Plenary Speaker:	Prashant Sardeshmukh, NOAA/CIRES, U. of Colorado at Boulder
Panelists:	Dale Durran, The University of Washington
	Nicole Lovenduski, The University of Colorado at Boulder
	Emanuele Di Lorenzo, The Georgia Institute of Technology
	Marika Holland, NCAR

2:45 PM   Break

3:15   **Exploring Predictability through New Methodologies and Technologies**

This session will focus on technological advances and other new methodologies and approaches – from machine learning to coupled data assimilation – that can help advance theoretical understanding of predictability and inform the development of models that more accurately represent the coupled Earth system and its predictability.

Chair:	Jeanine Jones, California Department of Water Resources
Plenary Speaker:	Elizabeth (Libby) Barnes, Colorado State University
Panelists:	Jeff Anderson, NCAR
	Michael Dietze, Boston University
	Gudrun Magnusdottir, The University of California, Irvine
	Tapio Schneider, The California Institute of Technology

4:45 PM   **Synthesis/report out**
Amanda Staudt, NASEM

5:00 PM   **Adjourn**

June 5, 2020

*All time is Eastern Daylight Time (EDT)

11:00 AM   **Welcome back**
Jim Hurrell, Chair of the ESP R&D Organizing Committee

11:05 AM   **Optimizing Observations to Explore Predictability**

The observation and study of key processes is crucial to advance theoretical understanding of predictability and also to improve the modeling of those processes. This session will identify opportunities to take a much more deliberate approach to observations in the context of Earth system predictability research and development.

Chair:	Gabriele Pfister, NCAR
Plenary Speaker:	Sarah Gille, The University of California, San Diego
Panelists:	Klaus Keller, The Pennsylvania State University
	Joellen Russell, The University of Arizona
	Jim Randerson, The University of California, Irvine
	Peter Neilley, IBM/The Weather Company

12:35 PM   Break

1:00 PM   **A Holistic Earth System Modeling Framework**

Our current understanding of predictability limits is based on imperfect models and incomplete understanding and representation of critical processes that are key to making skillful predictions. As such, the upper bounds of Earth system predictability are difficult to quantify. This session will focus on the necessity to better integrate predictability research with Earth system model development and application.

Chair:	Scott Doney, The University of Virginia
Plenary Speaker:	Jean-Francois Lamarque, NCAR
Panelists:	Ruby Leung, DOE-PNNL
	Natalie Mahowald, Cornell University
	Charles Stock, NOAA/GFDL
	Cecilia Bitz, University of Washington

2:30 PM   Break

3:00 PM   **A New Research Framework for Practicable Earth System Predictability**

Development of a national approach and strategy to better connect predictability-focused theoretical work with observational, modeling and technology research is an imperative for advancing practicable prediction. How can we avoid the compartmentalization of communities to make convergent research the new normal, and how do we develop and sustain a creative workforce focused on the science and applications of Earth system predictability research?

Chair:	Jenni Evans, The Pennsylvania State University
Plenary Speaker:	Duane Waliser, NASA
Panelists:	Paula Bontempi, NASA/The University of Rhode Island
	Waleed Abdalati, NOAA/CIRES, U. of Colorado at Boulder
	Chris Bretherton, The University of Washington

4:30 PM   **Synthesis/report out**
                   Amanda Staudt, NASEM

4:45 PM   **Next Steps**
                   Kelly Oskvig, NASEM
                   Kelvin Droegemeier, Office of Science and Technology Policy

5:00 PM   **Adjourn**

Registered Participants - as of 1pm EDT, June 1, 2020

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Adria	Schwarber	American Institute of Physics
David	Seabrook	Retired
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Isla	Simpson	UCAR
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Xuehang	Song	PNNL
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Workshop on Earth System Predictability R&D
Committee Membership

James W. Hurrell
Colorado State University

James (Jim) Hurrell joined Colorado State University faculty in September 2018 as the Scott Presidential Chair in Environmental Science and Engineering and a professor in the Department of Atmospheric Science. Dr. Hurrell is a former director of the National Center for Atmospheric Research (NCAR) in Boulder, Colorado, where he was a Senior Scientist in the Climate and Global Dynamics Laboratory (CGD). He is also the former Chief Scientist of Community Climate Projects in CGD, which includes the Community Earth System Model, and a former director of CGD and the NCAR Earth System Laboratory. Dr. Hurrell's research has centered on empirical and modeling studies and diagnostic analyses to better understand climate, climate variability and climate change. He has authored or co-authored more than 100 peer-reviewed journal articles and book chapters, as well as dozens of other planning documents, workshop papers and editorials. Dr. Hurrell has been extensively involved in the World Climate Research Programme (WCRP) on Climate Variability and Predictability (CLIVAR), including roles as co-chair of the Scientific Steering Group of both U.S. and International CLIVAR, Chair of the Scientific Organizing Committee for the WCRP Open Science Conference (2011), and membership on several other CLIVAR panels. He is currently a member of the Joint Scientific Committee of WCRP. Dr. Hurrell has served on several National Academies panels, and he has provided briefings and testimonies to both the U.S. Senate and the House of Representatives on climate change science. He attended the April 2020 Roundtable on Earth System Predictability Research and Development, and moderated one of the panels.

Scott C. Doney
University of Virginia

Scott Doney is the first Joe D. and Helen J. Kington Professor in Environmental Change at the University of Virginia. His expertise spans oceanography, climate and biogeochemistry, with particular emphasis on the application of numerical models and data analysis methods to global-scale questions. Much of his research focuses on how the global carbon cycle and ocean ecology respond to natural and human-driven climate change. He is the author of nearly 300 peer-reviewed research publications and co-author of a textbook on data analysis and modeling methods for the marine sciences. Dr. Doney was the inaugural chair of the U.S. Ocean Carbon and Biogeochemistry Program, a convening lead author for the Oceans and Marine Resources chapter of the 2014 U.S. National Climate Assessment, member of a number of National Academies committees, and served on both the NSF Geosciences and NSF Environmental Research and Education Advisory Committees. He is the past Director of the Ocean and Climate Change Institute and Chair of Marine Chemistry and Geochemistry Department at the Woods Hole Oceanographic Institution (WHOI). He was awarded the James B. Macelwane Medal from the American Geophysical Union in 2000, WHOI Ocean and Climate Change Institute Fellow in 2003, an Aldo Leopold Leadership Fellow in 2004, the WHOI W. Van Alan Clark Sr. Chair in 2007, a AAAS Fellow in 2010, and the Huntsman Award for Excellence in Marine Science in 2013 from the Royal Society of Canada. Dr. Doney attended and was a panelist at the April 2020 Roundtable on Earth System Predictability Research and Development.

Jenni-Louise Evans
The Pennsylvania State University

Jenni-Louise Evans is the director of the Pennsylvania State University's Institute for CyberScience, professor of meteorology, and research fellow in Penn State's Institutes of Energy and the Environment. Dr. Evans and her team employ high performance computing for detailed dynamical modeling of tropical cyclones and extratropical events; ensemble forecasts and advanced statistical analyses of these storms; and studies of climate change impacts in the tropics and beyond. In her recent research, she has employed a variety of novel statistical methodologies for physically-based partitioning of ensemble forecasts of tropical cyclones, with the goal of advancing tropical cyclone forecast skill and fundamental understanding of these storms. Dr. Evans is a fellow and past president of the American Meteorological Society. She has served on the U.S. Science Steering Committee for the World Meteorological Organization THORPEX Pacific Asian Regional Campaign, the U.S. Weather Research Program Science Steering Committee, the advisory board for the NOAA/NSF Developmental Testbed Center (for operational and research numerical models), the NSF Advisory Group for EarthCube, and as editor of AMS Monthly Weather Review. Dr. Evans received a B.Sc. (honors) and a Ph.D. from Monash University in applied mathematics. She attended and facilitated a breakout group at the April 2020 Roundtable on Earth System Predictability Research and Development.

Jeanine A. Jones
California Department of Water Resources

Jeanine A. Jones is a principal engineer and interstate resources manager at the California Department of Water Resources. She received her M.S. in civil engineering from the California State University, Sacramento, and is a registered civil engineer in California and Nevada. Ms. Jones was responsible for preparation of the 1998 update of the California Water Plan and the 2000 Governor's Advisory Drought Planning Panel report. She also participated in negotiations for the 2003 Colorado River Quantification Settlement Agreement and related agreements with relevant states and local agencies, and currently participates in the Colorado River Basin States negotiations over drought and shortage management. Her statewide planning and drought management responsibilities included actions to inform the public about California drought vulnerability and to mitigate its effects. Such actions require the collection and analysis of regional data on parameters of interest to the Climate Change Science Program, including land use, water use, water supply, and surface and groundwater hydrology. Ms. Jones has served on the Colorado River Board of California and on a variety of committees of the Western States Water Council. She was also a Governor's liaison to the Western Water Policy Review Advisory Commission. She attended the April 2020 Roundtable on Earth System Predictability Research and Development.

Brad R. Colman
The Climate Corporation

Brad R. Colman is the Director of Weather Strategy for The Climate Corporation. In this role, he oversees and guides the design and execution of the Bayer & Climate Enterprise weather programs. The program spans across global weather stations, data acquisition and validation, data repository architecture and dissemination, and domain expertise. Central to this effort is Dr. Colman's close collaboration with The Climate Corporation's Weather Science Team (a team of statisticians, machine learners, and

atmospheric scientists), which develops unique weather, climate, and decision support information for the global agricultural industry. Previously, Dr. Colman worked for nearly two years on a Microsoft team chartered to grow a new Microsoft consumer weather service to serve the entire Microsoft ecosystem. Prior to joining the private sector, Dr. Colman enjoyed a long and diverse career with NOAA where he worked at The National Weather Service's forecast office in Seattle, Washington; NOAA's Environmental Research Laboratory in Boulder, Colorado; and was the Acting Director of NOAA's Meteorological Development Laboratory in Silver Spring, Maryland. Dr. Colman is an Affiliate Associate Professor in Atmospheric Sciences at the University of Washington. Dr. Colman holds a Sc.D. in Atmospheric Sciences from the Massachusetts Institute of Technology and a B.S. in Earth Sciences and Mathematics from Montana State University. He is a member and Fellow of the American Meteorological Society, and has served in a number of different roles within the Society. Dr. Colman is a member of the Washington State Academy of Sciences and is currently Co-Chair of NOAA's Science Advisory Board's Environmental Information Services Working Group. He attended and facilitated a breakout group at the April 2020 Roundtable on Earth System Predictability Research and Development.

Gabriele Pfister
National Center for Atmospheric Research

Gabriele Pfister is Deputy Director of the National Center for Atmospheric Research (NCAR) Atmospheric Chemistry Observations and Modeling Lab and Scientist III**.** Her general research is in studying the composition of the troposphere using satellite and in-situ observations (e.g., aircraft and ground-based measurements taken during field campaigns) in conjunction with regional and global atmospheric models. She serves as a science advisor for the South Coast Air Quality Management Plan Scientific Technical Modeling Peer Review Group, serves on the WRAP Regional Technial Operations Work Group, and was Co-PI on the NSF/NCAR Front Range Photochemical Experiment that took place in summer 2014. Dr. Pfister received her Ph.D. in Meteorology and Geophysics from Karl-Franzens University in Graz, Austria.

National Academies of Sciences, Engineering, and Medicine Staff:

Kelly Oskvig is a Senior Program Officer for the Division of Earth and Life Sciences' Ocean Studies Board where she applies her experiences in scientific program management, water quality, and oceanography to advance the board's priorities regarding ocean conservation issues. Kelly began her career at the Academies' with the Gulf Research Program. leading the Safer Offshore Energy Systems initiative and the Understanding Gulf Ocean Systems program.
Prior to the Academies, Kelly worked for the Integrated Ocean Drilling Program in Washington, DC. Kelly also spent much of her early career in Houston, Texas, working for the oil and gas industry as both a geotechnical engineer and a physical oceanographer. She has Bachelors' degree in Civil Engineering from the University of Texas at Austin and a Master's degree from Texas A&M in Physical Oceanography.

Amanda Staudt directs the Board on Atmospheric Sciences and Climate (BASC) and the Polar Research Board (PRB) at the National Academies of Sciences, Engineering, and Medicine. BASC and PRB conduct studies and convene workshops on emerging science and provide advice to the US government and the nation related to climate change, weather, air pollution, the Arctic, and Antarctica. Her team provides stewardship for the Academies' ongoing advice to the U.S. Global Change Research Program, leads a new Academies-wide Climate Communication Initiative, and recently completed a large study to

develop a Research Agenda for Carbon Dioxide Removal and Reliable Sequestration. Prior to taking on this role, Dr. Staudt was a Senior Climate Scientist at the National Wildlife Federation, where she focused on communicating climate science and impacts, developing the intellectual and practical foundation for climate-informed conservation, and advancing climate change science education. Dr. Staudt received her B.A. in environmental science and engineering and her Ph.D. in atmospheric sciences from Harvard University.

Workshop on Earth System Predictability R&D

Participant Bios

Waleed Abdalati is Director of the Cooperative Institute for Research in Environmental Sciences (CIRES) at the University of Colorado and a Professor in the university's Department of Geography. CIRES, established through a cooperative agreement with the National Oceanic and Atmospheric Administration (NOAA), is a diverse institute that focuses on understanding the Earth System and its components, as well as the human relationship with our environment. His research interests are in the use of satellite and airborne remote sensing techniques, integrated with in situ observations and modeling, to understand how and why the Earth's glaciers and ice sheets are changing and the implications for sea level rise. This work has taken him to the Arctic, the Antarctic and the Patagonian Ice Fields ten times. Before joining CIRES in 2008, Dr. Abdalati held various positions at NASA in the areas of scientific research, program management, scientific management, mission science oversight, etc. In 2011 and 2012, he served as NASA Chief Scientist, acting as advisor on agency science matters to the NASA Administrator and NASA leadership, and working with the White House and Congress on matters related to the NASA Science portfolio. Earlier in his career, he worked as an engineer in the aerospace industry. His technical and scientific expertise is complemented by considerable experience communicating with the public, the media, and NASA sponsors and stakeholders. Dr. Abdalati received a B.S. in Mechanical Engineering from Syracuse University in 1986, a M.S. in Aerospace Engineering and a Ph.D. in Geography from the University of Colorado in 1991 and 1996 respectively. Dr. Abdalati is a Fellow of the American Association for the Advancement of Science and has received over a dozen professional awards from the White House, NASA, NSF and The American Institute for Aeronautics and Astronautics.

Jeffrey "Jeff" Anderson is Section Head of NCAR's Data Assimilation Research Section (DAReS). His research career has spanned two decades and has been focused by the common theme of improving predictions of the earth's atmosphere. He has made research contributions in theoretical geophysical fluid dynamics, seasonal prediction, predictability, ensemble prediction and ensemble data assimilation. Jeff's accomplishments in software engineering, applied mathematics and statistics have been directly in support of his goal to improve prediction. Together, Jeff and his DAReS colleagues aim to continue to advance the theory and practice of ensemble data assimilation. In addition, they have successfully accelerated the progress of many other NCAR projects by providing centralized data assimilation expertise which can be coordinated with existing observational and modeling expertise.

Elizabeth "Libby" Barnes is an associate professor of Atmospheric Science at Colorado State University. She joined the CSU faculty in 2013 after receiving dual B.S. degrees (Honors) in Physics and Mathematics from the University of Minnesota, obtaining her Ph.D. in Atmospheric Science from the University of Washington, and spending a year as a NOAA Climate & Global Change Fellow at the Lamont-Doherty Earth Observatory. Her research is focused on large-scale atmospheric variability and the data analysis tools used to understand its dynamics. Topics of interest include jet-stream dynamics, Arctic-midlatitude connections, subseasonal-to-seasonal (S2S) prediction of extreme weather events, health-related climate impacts, and data science methods for climate research (e.g. machine learning, causal discovery). She teaches graduate courses on fundamental atmospheric dynamics and data science and statistical analysis methods. Elizabeth is also involved in a number of research community activities. In addition to being the lead of the new US CLIVAR Working Group: Emerging Data Science Tools for Climate Variability and Predictability, she is also the lead for the NOAA MAPP S2S Prediction Task Force,

an Associate Editor of *Journal of Climate*, and an Editorial Board Member for *npj Climate and Atmospheric Science*. She also serves on the advisory panel for the Atmospheric Chemistry Observations and Modeling (ACOM) Laboratory at NCAR, the NSF Arctic Sciences Section Portfolio Review Committee, the AMS AOFD Committee, and is a member of the International Commission on Dynamical Meteorology, a Commission of the IAMAS. Elizabeth has received numerous awards over the course of her career including the 2020 AMS Clarence Leroy Meisinger Award and an NSF CAREER grant in 2018.

Cecilia Bitz is Professor and Chair of the Atmospheric Sciences Department at the University of Washington, and she is part of the UW Program on Climate Change. Dr. Bitz's research focus is on climate and climate change in the high latitudes, climate modeling, and Earth system predictability. She is currently working on Arctic sea ice predictability, the sea ice-wave interactions in the Antarctic, predicting pollen concentrations, and data assimilation. She has traveled to both the Arctic and Antarctic to make measurement to understand polar climate physics and improve predictive models. Dr. Bitz earned her PhD in 1997 from the department of her current position. Dr. Bitz is a member of the Board on Atmospheric Sciences and Climate of the National Academies and has served on study groups that wrote reports titled "Next Generation Earth System Predictions: Strategies for Subseasonal to Seasonal Forecasts" and "National Security Implications of Climate Change for U.S. Naval Forces." She was a Fulbright Scholar to New Zealand during her last sabbatical.

Paula Bontempi has been a biological oceanographer for 25 years. She began her career as a research intern at the New England Aquarium as an undergraduate at Boston College, later entering the fields of phytoplankton taxonomy and physiology in the Department of Oceanography at Texas A&M University. Research on phytoplankton taxa and coupled physical and biological drivers of global and regional phytoplankton spatial patterns led to interests in marine bio-optics and ocean color remote sensing. She graduated from the University of Rhode Island's Graduate School of Oceanography in 2001 with a Ph.D., spending time during her studies as a research fellow at the SACLANT Lab in La Spezia, Italy, in Friday Harbor, Washington, and as a summer intern at NASA's Goddard Space Flight Center. She moved from the faculty at the University of Southern Mississippi's Department of Marine Science to NASA Headquarters in 2003. Dr. Bontempi spent over 16 years as the program manager for Ocean Biology and Biogeochemistry at NASA Headquarters, as well as the Lead for NASA's Carbon Cycle and Ecosystems Focus Area and the agency's Carbon Cycle Science research lead, before becoming the Earth Science Division's Acting Deputy Director in 2019. She is Program Scientist for MODIS-Terra and Aqua, Suomi NPP, PACE, NAAMES (EV-S), HICO, CORAL (EV-S), and the former SeaWiFS mission. She has been honored to be invited to teach the Earth Science module of NASA's astronaut training class over the last several years.

Chris Bretherton is an atmospheric scientist who studies cloud formation and turbulence and improves how they are simulated in global climate and weather forecast models. His group at UW has pioneered machine learning strategies for parameterization of cloud processes in climate models and the application of global cloud-resolving modeling to improve the representation of clouds, aerosol and precipitation processes. He co-leads a new climate modeling initiative at Vulcan Inc. in Seattle that is continuing this work in collaboration with GFDL to improve prediction of precipitation on all time scales from days to decades in their suite of weather and climate models. His research also includes participating in field experiments and observational analyses, three-dimensional modeling of fluid flow in and around fields of clouds, and understanding how clouds will respond to and feed back on climate change. Computer code developed by his research group for simulating cloud formation by atmospheric turbulence is used in the two leading US climate models. He was a lead author of the Intergovernmental Panel on Climate Change Fifth Assessment Report in 2013, Chair of a 2012 National Academy report

entitled *A National Strategy for Advancing Climate Modeling*, and a former director of the University of Washington Program on Climate Change. In 2012, he received the Jule G. Charney Award, one of the two highest career awards of the American Meteorological Society, and he was the 2019 AMS Haurwitz Lecturer. He is a Fellow of the AMS and AGU, and a member of the National Academy of Sciences and Washington State Academy of Sciences.

Michael Dietze leads the Ecological Forecasting Laboratory at Boston University, whose mission is to better understand and predict ecological systems, and is author of the book "Ecological Forecasting". He is interested in the ways that iterative forecasts, which are continually confronted with new data, can improve and accelerate basic science in ecology, while at the same time making that science more directly relevant to society. Much of the current work in the lab is organized within the Near-term Ecological Forecasting Initiative (NEFI) and the PEcAn project. NEFI is focused on addressing overarching questions about ecological predictability, while developing forecasts for a wide range of ecological processes (vegetation phenology and land-surface fluxes; ticks, tick-borne disease and small mammal hosts; soil microbiome; aquatic productivity and algal blooms) and advancing statistical and informatic tools for ecological forecasting. PEcAn is focused on the terrestrial carbon cycle, improving our capacity for carbon MRV (monitoring, reporting, verification), forecasting, data assimilation, and multi-model benchmarking and calibration within the land component of Earth System models.

Emanuele Di Lorenzo is a Professor of Ocean and Climate Dynamics and the Director of the Program in Ocean Science and Engineering (OSE) at the Georgia Institute of Technology's School of Earth and Atmospheric Sciences. His research interests include oceanography, climate dynamics, inverse and ocean modeling, and ecosystems and climate change. Emanuele has received several awards over the course of his career, including the North Pacific Marine Science IGO PICES SB Award in 2013, and to date, his 100+ publications have been cited nearly 6,000 times. He has also been recognized with a number of national and international distinctions, including Chairmanship of the PICES Physical Oceanography and Climate Committee, Co-Chairmanship of the US CLIVAR Phenomena, Observations, and Synthesis Panel, and Membership on the US CLIVAR Science Steering Committee (2017-present). Emanuele received his Ph.D. in Climate Sciences from the Scripps Institution of Oceanography at the University of California San Diego in 2003.

Kelvin Droegemeier serves as Director of The White House Office of Science and Technology Policy (OSTP). Before joining the white house, Kelvin served as Vice President for Research and Regents' Professor of Meteorology at the University of Oklahoma. He also co-founded, directed, and led the National Science Foundation (NSF) Science and Technology Center for Analysis and Prediction of Storms (CAPS) and served as co-founder and Deputy Director of the NSF Engineering Research Center for Collaborative Adaptive Sense of the Atmosphere (CASA). Kelvin served two six-year terms on the National Science Board, the governing body of the NSF, including the last four years as Vice-Chairman, having been nominated by Presidents George W. Bush and Barack Obama and twice confirmed by the United States Senate. He has also served on and chaired numerous national boards and committees and is a Fellow of the American Meteorological Society and American Association for the Advancement of Science. He was appointed in 2017 as Oklahoma Cabinet Secretary of Science and Technology.

Dale Durran is a Professor of Atmospheric Sciences and Adjunct Professor of Applied Mathematics at the University of Washington. His current focuses include atmospheric predictability, mountain meteorology, atmospheric waves, machine learning and numerical methods for the computer simulation of these phenomena. Dale's dedicated research has seen him receive the Naval Research Laboratory's Alan Berman Research Publication Award in 2002 and 2007, the AMS Mountain Meteorology Committee's Mountain Meteorology Award in 2014, and current recognition as a Fellow of

the American Meteorological Society (AMS). He has also served on a range of committees and review panels, including terms as chair of the AMS' Committees on Mountain Meteorology and on Mesoscale Processes. Dale received a B.S. in Mathematics from California State University at San Luis Obispo in 1974, a M.S. in Mathematics from the University of California at Berkeley in 1975, and a Ph.D. in Meteorology from MIT in 1981.

Sarah Gille is a professor in the Oceans and Atmospheres Section at Scripps Institution of Oceanography, University of California, San Diego (UCSD). Her research focuses on ocean dynamics and their role in Earth's climate system, primarily in the Southern Ocean. She makes use of a combination of remote-sensing data, in situ observations, numerical model output, and theoretical ideas. Gille received a B.S. in physics from Yale University and a Ph.D in physical oceanography from the Massachusetts Institute of Technology (MIT)–Woods Hole Oceanographic Institution Joint Program in 1995. She carried out postdoctoral research at Scripps and at the University of East Anglia (UK). Before joining Scripps and UCSD in 2000, Gille was an assistant professor in the Department of Earth System Science at the University of California, Irvine. She is a fellow of the American Geophysical Union, and a member of a number of other professional organizations, including the American Meteorological Society and The Oceanography Society. In 2000, she received the Zeldovich Award for excellence and achievement by a young scientist from the Committee on Space Research and the Russian Academy of Sciences as well as a Career Award from the National Science Foundation. In 1995, she received the Carl-Gustav Rossby Award for best thesis of the year from MIT's Program in Atmospheres, Oceans, and Climate.

Marika M. Holland is a Senior Scientist in the Climate and Global Dynamics Laboratory at the National Center for Atmospheric Research (NCAR). Her research is focused on the role of sea ice in the climate system, including long-term sea ice change, sea ice predictability, and polar climate variability. Dr. Holland has also been involved in work assessing the biological impacts of changing polar climate conditions. She has extensive experience in using climate models to study climate variability and change and has been active in the development of improved sea ice models for climate simulations. Dr. Holland has served as co-chair for the Polar Climate Working Group of the Community Earth System Model and Chief Scientist for the Community Earth System Model project. She is a contributing author on the Intergovernmental Panel on Climate Change third, fourth, and fifth assessment reports, has contributed to numerous other assessments on the changing polar climate, and is an author on over 100 peer-reviewed publications. Dr. Holland received her Ph.D. in Atmosphere and Ocean Sciences from the University of Colorado and was a Postdoctoral Fellow at the University of Victoria in British Columbia before joining the scientific staff of NCAR.

Sarah Jones is director of research and development and member of the Executive Board at Deutscher Wetterdienst (DWD), the German Weather Service based in Offenbach. A native of the United Kingdom, her interest in weather forecasting was piqued by time spent on the water in her youth, specifically, practicing regattas on an inland lake near Liverpool. She began to take an interest in how the atmosphere works, how weather develops, and how the predictive analytics of weather forecasting can play a beneficial role in our daily lives. Jones' determined pursuit of knowledge in her chosen field led to a BSc in Physics, followed by a PhD in meteorology with a focus on heavy rain in mid-latitude frontal systems. Soon after receiving her advanced degree, she jumped at the opportunity to research hurricanes at the University of Munich. Historically, computer models have had difficulty predicting how these storm systems will affect the weather in Europe, and yet Jones relished the challenge. In 2004, she joined the Institute for Meteorology and Climatology in Karlsruhe as a professor overseeing research projects with a focus on understanding how high impact weather systems develop and what limits our ability to predict them. These include thunderstorm systems in Africa - generally, researchers have found that hurricanes originate on the African coast, arc across the Atlantic to the Caribbean, and from

there, migrate back across the ocean to Europe. In 2011, she accepted the role as head of research and development at the German Weather Service, with the overall responsibility for coordinating research across the organization as well as managing a team of around 200 employees. International collaboration is essential for her research as well. In 2015 she became Chair of the World Meteorological Organization (WMO) World Weather Research Programme and in 2019 Vice Chair of the new WMO Research Board. Though the ability to predict the weather has greatly improved since she first began her research, Jones knows that society's need for tailored information from prediction systems will increase and climate change will act as an ever-evolving threat in the years ahead. One of DWD's key strategic initiatives, "SINFONY," aims to address this issue head-on by improving short term forecasting that will enable informed decision-making and preparation for increasingly variable weather.

Klaus Keller is a Professor of Geosciences at The Pennsylvania State University where he also directs the Center for Climate Risk Management. Before joining Penn State, he worked as a research scientist and lecturer at Princeton University and as an engineer in Germany. Professor Keller graduated from Princeton with a Ph.D. in civil and environmental engineering. He received master's degrees from M.I.T. and Princeton as well as an engineer's degree from the Technische Universität Berlin. His research addresses two interrelated questions. First, how can we mechanistically understand past and potentially predict future changes in the Earth system? Second, how can we use this information to design sustainable, scientifically sound, technologically feasible, economically efficient, and ethically defensible risk management strategies? He analyzes these questions by mission-oriented basic research covering a wide range of disciplines such as Earth system science, economics, engineering, philosophy, decision science, and statistics. He contributed to reports from the Intergovernmental Panel on Climate Change, co-edited an open source textbook, and published more than 100 peer-reviewed studies.

Jean-François Lamarque is currently the Director of the Climate and Global Dynamics Laboratory of NCAR. He majored in Physics, graduating in 1987 followed by a Ph. D. in Physics awarded in January 1993, both at the Catholic University of Louvain (Belgium). He came to NCAR in 1990 under a Graduate Research Assistantship of the Advanced Study Program. He has been at NCAR since, except for a one-year position at NOAA-Boulder in 2008-2009. His research interests center on the impact and behavior of atmospheric chemistry in the Earth system and his focus is on long-term trends in atmospheric composition. As part of the Climate Model Intercomparison Project Phase 5 (CMIP5, in support of International Panel on Climate Change Assessment Report #5, IPCC AR5), he has led, in collaboration with D. Shindell (NASA), the Atmospheric Chemistry and Climate Model Intercomparison Project (ACCMIP). He is one of the co-leads of the on-going AerChemMIP project under CMIP6. He is the incoming chair of the Climate Model IntercomparisonProject (CMIP). He has led the development of atmospheric chemistry in the Community Earth System Model (CESM) and was the CESM Chief Scientist from 2014 to 2018. He is the author or co-author of over 275 peer-reviewed publications. He was a Lead Author (Chapter 8, Radiative forcing) and Contributing Author (Chapter 6, Carbon and other Biogeochemical Cycles) of the IPCC AR5.

L. Ruby Leung is a Battelle Fellow at Pacific Northwest National Laboratory and an Affiliate Scientist at National Center for Atmospheric Research. Her research broadly cuts across multiple areas in modeling and analysis of climate and the hydrological cycle including precipitation, land-atmosphere interactions, orographic processes, monsoon climate, extreme events, land surface processes, and aerosol-cloud interactions. Dr. Leung is the Chief Scientist of Department of Energy's Energy Exascale Earth System Model (E3SM). The E3SM project involves over 120 earth system and computational scientists to develop state-of-the-art capabilities for modeling human-earth system processes on DOE's next generation high performance computers. She has organized key workshops sponsored by DOE, NSF, NOAA, and NASA, and served on advisory panels and an NRC committee to define future priorities in

climate modeling, hydroclimate, and water cycle research. She is an editor of the American Geophysical Union *Journal of Geophysical Research—Atmospheres* and American Meteorological Society *Journal of Hydrometeorology*. She is a member of the National Academy of Engineering and Washington State Academy of Sciences, and a council member of the American Meteorological Society. Dr. Leung is the recipient of the American Geophysical Union Global Environmental Change Bert Bolin Award and Lecture in 2019. She has published over 350 peer-reviewed journal articles.

Nicole "Nikki" Lovenduski is an Associate Professor of Atmospheric and Oceanic Sciences at the University of Colorado at Boulder specializing in the marine carbon cycle, climate variability, and ocean modeling. Her research interests include modeling and observation of ocean biogeochemistry, polar climate change and its impact on the oceans, global carbon cycle dynamics, and global climate modeling. Nikki aims to improve our understanding of the ocean's role in the global carbon cycle by investigating the physical, chemical, and biological processes controlling air-sea CO_2 exchange. She studies how these processes operated in the past, how they function today, and how they might respond to anthropogenic climate change in the future. To do this, she employs a hierarchy of ocean and Earth system models along with satellite and in situ observations. To date, Nikki's efforts have resulted in a wide range of publications and numerous awards, including but not limited to recognition as a National Academy of Sciences Kavli Frontiers of Science Fellow in 2018, and the American Geophysical Union's Ocean Sciences Early Career Award in 2019. Nikki received her B.A. in Earth and Planetary Sciences from Washington University in St. Louis in 2001, followed by an M.S. and Ph.D. in Atmospheric and Oceanic Sciences from UCLA in 2003 and 2007, respectively.

Gudrun Magnusdottir is an expert in atmospheric and climate dynamics, atmosphere and ocean interactions, and atmosphere and sea-ice interactions. She uses a combination of observations and a hierarchy of numerical models to study dynamical processes in the atmosphere, and climate variability. Much of her research is focused on understanding processes that can lead to extended predictive skill of atmospheric phenomena, including extreme events, by considering the slower components of the climate system, not only surface processes (such as ocean, sea ice and snow) but also stratospheric circulations that through stratosphere-troposphere coupling can improve predictive skill on seasonal time scales. Professor Magnusdottir has a BS in Physics from the University of Iceland. After obtaining an M.S. degree in atmospheric science at Colorado State University, she briefly worked as a meteorologist in the Icelandic Meteorological Office. She obtained a Ph.D. from Colorado State University. Prior to joining the faculty at UC Irvine, she was a postdoctoral researcher at DAMTP at the University of Cambridge. She has also served on the faculty of the Geophysical Institute at the University of Bergen in Norway. Professor Magnusdottir currently serves as an editor for Geophysical Research Letters of the American Geophysical Union, she is on the Scientific Steering Committee of US CLIVAR, she is a member of the Board of Trustees of the University Corporation for Atmospheric Research, she is on the American Meteorological Society's Committee for Climate Variability and Change and she is on the Advisory Board of the Energy Exascale Earth System Model (E3SM) Program.

Natalie Mahowald has undergraduate degrees in German and physics from Washington University, an M.S. in natural resource policy from the University of Michigan, and a Ph.D. in meteorology from Massachusetts Institute of Technology. Mahowald conducted her postdoctoral research at Stockholm University in Sweden prior to holding a faculty position at the University of California, Santa Barbara from 1998-2002. She then spent five years as a scientist at the National Center for Atmospheric Research (NCAR) before joining Cornell as a faculty member in 2007. Mahowald's research group is focused on understanding feedbacks in the earth system that impact climate change. This includes global and regional scale atmospheric transport of biogeochemically important species such as desert

dust, as well as the carbon cycle. The group looks at these issues through a combination of 3-dimensional global transport and climate models, as well as analysis of satellite and in situ data.

Nathan Mantua is a Supervisory Research Physical Scientist who currently leads the Landscape Ecology Team at NOAA's Southwest Fisheries Science Center in Santa Cruz, California. Previously, at the University of Washington in Seattle from 1995-2012, Nate co-directed the Climate Impacts Group and was an associate professor in the School of Aquatic and Fishery Sciences. His research interests include climate variability and predictability, climate impacts on natural resources, and the use of climate information in resource management. His lifelong interest in Pacific salmon and steelhead has had a major impact on his research and service activities. Nate has a B.Sc. in atmospheric sciences from UC Davis, and a PhD in atmospheric sciences from the University of Washington. He was a postdoctoral fellow at the Scripps Institute for Oceanography in a project focused on seasonal climate forecasting. He received NOAA's Presidential Early Career Award for his work on the Pacific Decadal Oscillation and its impacts on Pacific salmon in 2000.

Peter Neilley is Senior Vice President of Global Forecasting Services at The Weather Company. He is responsible for the research and development of next-generation capabilities that drive all weather and weather-dependent content for the company. He is the former chair of the American Meteorological Society's committee on weather analysis and forecasting, and current co-chair of the committee reviewing and advising NOAA on its overall environmental prediction capabilities. Late in 2019, Peter testified before Congress on the state of weather and climate forecasting in the U.S., and optimal pathways toward its improvement. He is an IBM Distinguished Engineer, a member of the Academy of Technology, and a fellow of the American Meteorological Society. He has a bachelor's degree in meteorology from McGill University (1982), and master's (1984) and Ph.D. (1990) from the Massachusetts Institute of Technology.

Roger S. Pulwarty is the Senior Scientist in the NOAA Physical Sciences Laboratory in Boulder, Colorado. His 100+ articles, book chapters, and technical reports focus on weather, water and climate, information services, and resilience in the U.S., Latin America and the Caribbean. Roger has helped develop and lead widely-recognized interdisciplinary science and risk management programs, including the Regional Integrated Sciences and Assessments, the National Integrated Drought Information System, the GEF Mainstreaming Adaptation program in the Caribbean, and the IAI Collaborative Research Network on Eastern Pacific Boundary Currents. Roger has served as a convening lead author (cla) on the IPCC WGII and Special Reports, the UN Office of Disaster Risk Reduction (UNDRR) Reports, and the US National Climate Assessments. He is a cla on forthcoming national interagency, European Union, and UNDRR disaster risk reduction assessments. Roger has served on scientific committees of the National Academy, provided testimonies before the U.S. Congress, and in advisory roles on science, services, and adaptation to the Western Governors Association, the WMO, the Organization of American States, OECD, and the InterAmerican and World Banks, among others. Roger's work on integrating science into decision-making has been featured in several media communications, including the New York Times, National Geographic, Forbes, and the BBC, and has been awarded by NOAA, the Department of Commerce, the AGU, the AMS, and the Caribbean Academy of Sciences. He is the co-editor of "Hurricanes: Climate and Socio-economic Impacts" (Springer, reissued in paperback 2012) and "Drought and Water Crises" (CRC Press, 2017).

James "Jim" Randerson is the Ralph J. and Carol M. Cicerone Professor of Earth System Science at the University of California, Irvine. Jim studies the global carbon cycle using remote sensing and in-situ

measurements and different types of models. Current research themes in his laboratory include climate-carbon cycle feedbacks, land use change, and the effects of fire on ecosystem function and atmospheric composition. He has conducted field work in Alaska and Siberia to assess the long-term impacts of fire on surface energy exchange and fluxes of carbon dioxide. In 2005, Jim was the recipient of the James B. Macelwane Medal awarded by the American Geophysical Union for "significant contributions to the geophysical sciences by an outstanding young scientist." He received a Ph.D. in Biological Sciences (1998) and a B.S. in Chemistry (1992) from Stanford University. He conducted work as a postdoctoral scholar at University of California, Berkeley and University of Alaska. He is a Fellow of the American Geophysical Union and a member of the US National Academy of Sciences.

Andrew "Andy" Robertson is a Senior Research Scientist and Head of the International Research Institute (IRI) Climate Group at Columbia University. After graduating from the University of Leeds, UK, with a BS in mathematics and geography, he received an MS from Imperial College, London in atmospheric physics and dynamics, and a PhD in atmospheric dynamics from the University of Reading in 1984, under the supervision of Brian Hoskins. Andy held postdoctoral and research positions at the Universities of Paris, Munich, and UCLA prior to joining the IRI in 2001. Now the author of over 90 peer-reviewed publications, Andy's research interests include: regional climate variability, predictability and change; probabilistic daily rainfall modeling; predictability of weather-within-climate; climate downscaling methodologies; tailoring of climate information for use in conjunction with sectoral models for climate adaptation and risk management. Andy also teaches in the Master of Arts Program in Climate and Society in the Department of Earth & Environmental Sciences, and he serves as a co-chair of the WWRP/WCRP Subseasonal to Seasonal Prediction Project.

Joellen Russell is the Thomas R. Brown Distinguished Chair of Integrative Science and Professor at the University of Arizona in the Department of Geosciences. Her research uses global climate and earth system models to simulate the climate and carbon cycle of the past, the present and the future, and develops observationally-based metrics to evaluate these simulations. Prof. 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 Intercomaprison Project (SOMIP). She currently serves as Co-chair of the NOAA Science Advisory Board's Climate Working Group, as an Objective Leader for the Scientific Committee on Antarctic Research's AntarcticClimate21, and on the National Center for Atmospheric Research's Community Earth System Model Advisory Board. Prof. Russell is one of the 14 scientists behind an amicus curiae brief supporting the plaintiff in the historic 2007 U.S. Supreme Court decision on carbon dioxide emissions and climate change, Commonwealth of Massachusetts, et al. v. U.S. Environmental Protection Agency. 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). She received her A.B. in Environmental Geoscience from Harvard and her PhD in Oceanography from Scripps Institution of Oceanography, University of California, San Diego. Joellen Russell's work on the westerly winds led to the creation of a new paradigm in climate science, namely that warmer climates produce stronger westerly winds. This insight solved one of the long-standing climate paradoxes, the mechanism responsible for transferring one-third of the carbon dioxide in the atmosphere into the ocean and then back out again during our repeated glacial-interglacial cycles.

Prashant Sardeshmukh is a Senior Research Scientist at the Cooperative Institute for Research in Environmental Sciences (CIRES) at the University of Colorado Boulder. Since receiving his Ph.D. from Princeton University in 1982, he has enjoyed a career as a climate dynamicist with broad interests in the diagnosis, modeling, prediction, and potential predictability of large-scale weather and climate variations around the globe on time scales of days to centuries. As a member of the NOAA ESRL Physical

Sciences Laboratory, Prashant's current research focuses on the sensitivities of the global weather forecasting system used at the National Centers of Environmental Prediction (NCEP). His team is engaged in documenting and understanding the regional aspects of ongoing climate changes, especially changes in the statistics of extreme weather, and determining to what extent they are anthropogenic or consistent with natural climate variability. Prashant and his team are also interested in documenting and understanding the actual and potential skill of weather and climate predictions (which is inherently limited due to the chaotic nature of the system) and how current prediction systems need to be improved to achieve the potential skill.

Tapio Schneider is Professor of Environmental Science and Engineering at Caltech and Senior Research Scientist at NASA's Jet Propulsion Laboratory. His research is focused on understanding how the turbulent dynamics of the atmosphere, from clouds to large-scale weather systems, shape Earth's climate. He is currently leading the Climate Modeling Alliance, whose mission is to build the first climate model that automatically learns from data. Schneider received his M.Sc. in 1997 and Ph.D. in 2001 from Princeton University.

Charles A. Stock received his Ph.D. in Civil, Environmental and Ocean Engineering from Woods Hole Oceanographic Institution/MIT Joint Program and his M.S of Engineering in Environmental Fluid Mechanics and Hydrology from Stanford University. He began working at NOAA in 2007 as an associate research scholar with NOAA's GFDL and Princeton University. In 2010, Stock received the Presidential Early Career Award for Scientists and Engineers for innovative research at the frontiers of climate and ecosystem science. He is currently a research oceanographer at NOAA's GFDL.

Duane Waliser is Chief Scientist of the Earth Science and Technology Directorate at the Jet Propulsion Laboratory (JPL) in Pasadena, California, which formulates, develops, and operates of a wide range of Earth science remote sensing instruments for NASA's airborne and satellite program. His principal research interests lie in Earth system processes, observations and modeling; weather-climate linkages, particularly subseasonal to seasonal (S2S) variability; prediction and predictability; and the Earth's water cycle. His recent foci at JPL involves working within NASA and across agencies to enable and enhance societal benefits from our growing understanding, observing and modeling capabilities of the Earth System . He received a B.S. in physics and a B.S. in computer science from Oregon State University in 1985, an M.S. in physics from UC San Diego in 1987, and his Ph.D. in physical oceanography from the Scripps Institution of Oceanography at UC San Diego in 1992.

Olga Wilhelmi is a geographer with twenty years of experience working at the interface of atmospheric and social sciences and GIS. She is the Head of the GIS Program at the National Center for Atmospheric Research (NCAR) and is a Project Scientist in NCAR's Research Application Laboratory. Olga is a graduate of Lomonosov Moscow State University where she majored in Physical Geography. She completed her Ph.D. in the School of Natural Resources at the University of Nebraska-Lincoln in 1999. Her research interests span a wide range of topics in the weather, climate, and society interactions, with the main focus on societal risk, vulnerability and adaptive capacity to extreme weather events and climate change. Olga has published over 60 peer-reviewed articles, book chapters, and reports addressing societal aspects of weather extremes and climate change, urban heat and human health, drought and water management, and preparedness and response to flash floods and hurricane storm surge. Olga is a recipient of Esri's Special Achievement in GIS award, as well as the UCAR's Outstanding Accomplishment Awards for the Scientific Publication, Diversity, and Education and Outreach. She served as Editor of *Weather, Climate and Society* and a member of the American Meteorological Society Board on Societal Impacts. Olga's current work focuses on extreme heat and air quality impacts on human health, urban governance of the food-water-energy nexus, and the role of geovisualization in extreme weather risk communication.