S. HRG. 116–597

ATMOSPHERIC SCIENCE RESEARCH AND FORECASTING INNOVATION

HEARING

BEFORE THE

SUBCOMMITTEE ON SCIENCE, OCEANS, FISHERIES, AND WEATHER

OF THE

COMMITTEE ON COMMERCE, SCIENCE, AND TRANSPORTATION
UNITED STATES SENATE

ONE HUNDRED SIXTEENTH CONGRESS

FIRST SESSION

MAY 16, 2019

Printed for the use of the Committee on Commerce, Science, and Transportation

Available online: http://www.govinfo.gov

U.S. GOVERNMENT PUBLISHING OFFICE
52–696 PDF WASHINGTON : 2023

SENATE COMMITTEE ON COMMERCE, SCIENCE, AND TRANSPORTATION

ONE HUNDRED SIXTEENTH CONGRESS

FIRST SESSION

ROGER WICKER, Mississippi, *Chairman*

JOHN THUNE, South Dakota
ROY BLUNT, Missouri
TED CRUZ, Texas
DEB FISCHER, Nebraska
JERRY MORAN, Kansas
DAN SULLIVAN, Alaska
CORY GARDNER, Colorado
MARSHA BLACKBURN, Tennessee
SHELLEY MOORE CAPITO, West Virginia
MIKE LEE, Utah
RON JOHNSON, Wisconsin
TODD YOUNG, Indiana
RICK SCOTT, Florida

MARIA CANTWELL, Washington, *Ranking*
AMY KLOBUCHAR, Minnesota
RICHARD BLUMENTHAL, Connecticut
BRIAN SCHATZ, Hawaii
EDWARD MARKEY, Massachusetts
TOM UDALL, New Mexico
GARY PETERS, Michigan
TAMMY BALDWIN, Wisconsin
TAMMY DUCKWORTH, Illinois
JON TESTER, Montana
KYRSTEN SINEMA, Arizona
JACKY ROSEN, Nevada

JOHN KEAST, *Staff Director*
CRYSTAL TULLY, *Deputy Staff Director*
STEVEN WALL, *General Counsel*
KIM LIPSKY, *Democratic Staff Director*
CHRIS DAY, *Democratic Deputy Staff Director*
RENAE BLACK, *Senior Counsel*

SUBCOMMITTEE ON SCIENCE, OCEANS, FISHERIES, AND WEATHER

CORY GARDNER, Colorado, *Chairman*
TED CRUZ, Texas
DAN SULLIVAN, Alaska
RON JOHNSON, Wisconsin
RICK SCOTT, Florida

TAMMY BALDWIN, Wisconsin, *Ranking*
RICHARD BLUMENTHAL, *Connecticut*
BRIAN SCHATZ, Hawaii
GARY PETERS, Michigan

CONTENTS

WITNESSES

APPENDIX

ATMOSPHERIC SCIENCE RESEARCH AND FORECASTING INNOVATION

THURSDAY, MAY 16, 2019

U.S. SENATE,
SUBCOMMITTEE ON SCIENCE, OCEANS, FISHERIES, AND WEATHER,
COMMITTEE ON COMMERCE, SCIENCE, AND TRANSPORTATION,
Washington, DC.

The Subcommittee met, pursuant to notice, at 10:05 a.m. in room SD–562, Dirksen Senate Office Building, Hon. Cory Gardner, Chairman of the Subcommittee, presiding.

Present: Senators Gardner [presiding], Sullivan, Scott, Baldwin, Blumenthal, and Udall.

OPENING STATEMENT OF HON. CORY GARDNER, U.S. SENATOR FROM COLORADO

Senator GARDNER. Thank you so much. I will call this hearing to order.

Thank you to Ranking Member Baldwin for your work on the subcommittee. I look forward to serving with you and working with you in this capacity.

And thank you to the witnesses for being here today.

I would like to extend a special welcome to Dr. Waleed Abdalati from the Cooperative Institute for Research in Environmental Sciences, CIRES, which is based in Boulder, Colorado. One of the many positive aspects of getting this opportunity for the hearing today in the Senate is the ability to showcase the best of our great State, Colorado. And Dr. Abdalati is among the best in the country on issues related to climate science, and I am honored that you would be here today. I am thankful that you took the time to travel and join us.

Today's hearing is about atmospheric research and innovation. In short, it is about the work that so many of our scientists are doing to combat the threat of climate change. I believe in climate change. I believe in the consensus within the scientific community. I believe humans are contributing to climate change, and I believe we have work to do together to solve it.

Unfortunately, climate change has become a partisan weapon used for more fighting than as a topic of serious discussion. In reality, there is unreasonableness on both far ends of the spectrum, but much in the middle where we can agree.

Last Congress, I worked closely with my colleague, Senator Gary Peters from Michigan, to pass the American Innovation and Competitiveness Act, legislation that updated policies at the National

Science Foundation and the National Institute of Standards and Technology. Both of those agencies do work applicable to climate science.

After 18 months of hard bipartisan work, we passed that bill into law, the first major science legislation to pass the Commerce Committee and into law in nearly a decade.

It is going to take a lot of that kind of commitment and good will on both sides of the aisle to find reasonable solutions to climate change. I look forward to working with my colleagues to find a path forward in that regard while we are investing huge sums of money into clean energy resources here in the United States and continue to work to reduce emissions.

I am looking forward to hearing from the witnesses today and how the United States is investing in climate research, how it is helping us tackle the challenge of climate change, and how we can be engaging others around the world in pursuing similar approaches to science.

With that, I will turn it over to Senator Baldwin.

STATEMENT OF HON. TAMMY BALDWIN,
U.S. SENATOR FROM WISCONSIN

Senator BALDWIN. Thank you, Mr. Chairman. It is a pleasure to open the first hearing of the new Science, Ocean, Fisheries, and Weather Subcommittee with you and especially on a topic that is so important to both of our States, research that helps us better understand our changing climate and how our communities can respond to the challenges they face because of it.

I know our esteemed witnesses will describe the knowledge we have gained about this challenge that has impacts at the local level and across the globe. I believe it is critical that we use that information to support our communities as they face new and growing challenges to health, public safety, and economic stability. And as we review this information, this hearing is a perfect example of a guiding force in my state, something we call the Wisconsin Idea. It is the idea that public research is not intended to just gather dust on a shelf. Rather, its purpose is to improve the lives of the public, address threats to our economy, and to innovate to improve lives for the next generation.

This is urgently important right now as we are presented with an abundance of strong research findings that show that climate change is happening rapidly. We know that substantial and swift action is needed to reduce the impact of these changes, as well as to help our communities prepare for and recover from the increasingly intense weather events that impact our safety and economic stability.

I would like to talk a bit about the changes that we are seeing in my State and what they mean for the people of Wisconsin. We are seeing more extreme storm events. Infrastructure that has weathered storms for decades is now failing. Our infrastructure was not built to handle rain like the rain we are seeing. Bridges and roads are being washed away literally, people cutoff from life-saving services and urgent medical treatment. Heavy rain events are overwhelming our storm water systems, and this leads to more contamination released into our lakes and it threatens our drinking

water supplies. These are not inconveniences. These are fundamental and dangerous disruptions to people's lives. And after a bridge washes out, communities need the tools, funding, and information to build better and more resilient infrastructure that can withstand this new reality of more severe weather.

Many communities in Wisconsin are focused on building back stronger and more resilient because they know and live the realty of a changing climate every day, and they know the enormous local costs to taxpayers of having to replace infrastructure and manage public health and safety risks. It is our job to help give them the tools that they need to succeed.

Unfortunately, a lot of the tools communities have right now are delaying or even preventing actions to rebuild in a stronger and more resilient way. The disjointed Federal disaster response process can be hard for communities to navigate. Aid for rebuilding can be delayed, making it difficult to move forward with repairs critical to daily life. Sometimes regulations make it harder for communities to act on current information and make strategic investments for their future.

Climate change is certainly a big and global problem, but it is also just as importantly a very local reality. Things are changing. Communities are struggling to have the resources to stay ahead of those changes, and we need to do more.

Fortunately, people across Wisconsin and across the country are leading the way when Washington has failed to respond to these threats. Local leaders are championing infrastructure design for the very rainfall that their communities will face in the future and making investments now that use taxpayer dollars strategically and guard against future loss of life and property. Businesses are looking at these risks, implementing strategies to avoid losses from weather events, and the supply chain disruptions.

Our faith communities are also leading the way, acknowledging the important reality that people with less means will also be less able to protect themselves and their families from the costs of recovering from natural disasters, facing heat waves, and managing higher costs for food, water, and other necessities.

Mr. Chairman, I appreciate your leadership and having a discussion on this important research that gives our communities good information so they can make informed decisions for their future.

And now I would like to welcome a leader in research and community resiliency from Superior, Wisconsin, our own Dr. Erika Washburn. Dr. Washburn, I know that you and your team have helped respond to many emergencies across northern Wisconsin over the past several years from floods to water monitoring after a refinery explosion in your community. Our communities have been better equipped to react to these challenges because of your expertise and leadership. Thank you for the work you do and thank you for making the trip to share that expertise in this important discussion.

Senator GARDNER. Thank you, Senator Baldwin.

And to Dr. Bronk and Dr. Horton, if you want a special call-out in opening statements, you are going to have to move to Wisconsin or Colorado. All right?

[Laughter.]

Senator BALDWIN. Dr. Bronk hails from Wisconsin.

Senator GARDNER. Hails from Wisconsin. OK, very good. You are always welcome. So very good.

But I will just quickly introduce all the witnesses together. As I mentioned, Waleed Abdalati is the Director of the Cooperative Institute for Research in Environmental Sciences, also known as CIRES, in Boulder. Dr. Deborah Bronk, the President and CEO of Bigelow Laboratory for Ocean Sciences of East Booth Bay, Maine; and Dr. Radley Horton—welcome—Associate Research Professor at Lamont-Doherty Earth Observatory at Columbia University Earth Institute, Palisades, New York. And of course, as talked about by Senator Baldwin, Dr. Erika Washburn, Director of the Lake Superior National Estuarine Research Reserve in Superior, Wisconsin. I very, very much appreciate all of your willingness and testimony today, looking forward to our conversation.

And, Dr. Abdalati, if you would start, and then we will just go down the line. Thank you.

STATEMENT OF DR. WALEED ABDALATI, DIRECTOR, COOPERATIVE INSTITUTE FOR RESEARCH IN ENVIRONMENTAL SCIENCES, UNIVERSITY OF COLORADO BOULDER

Dr. ABDALATI. So thank you, Chairman Gardner and Ranking Member Baldwin and other distinguished members of the Committee, for inviting me to provide testimony at this important hearing.

I also thank you for your ongoing support of weather and drought-related research, which directly impacts our national economy, health, livelihood, and prosperity.

As was said, I am the Director of CIRES at the University of Colorado, and as part of our broad research portfolio, CIRES scientists directly support NOAA in its weather forecasting efforts and climate research by developing key insights into atmospheric and related phenomena, building modeling and analytical tools to improve forecasts and projections.

In the last 5 years, forecast model improvements made by NOAA and the research community have greatly improved forecasting of thunderstorms, blizzards, floods, and even smoke from wildfires. Forecast error has gone down 25 percent in that time, and we find even greater improvement in some areas. For example, our skill in pinpointing the location of precipitation has improved by 50 percent in the last 5 years.

Despite these successes, however, there remain critical needs for more accurate forecasts and better lead-time. In the longer term, seasonal and sub-seasonal forecasting and longer-term climate projections, as well as information at more local levels are needed.

Achieving these objectives requires continued development, maintenance, and operation of super computers, the effective use of cloud computing, and support for research on techniques such as improving code, advancing machine learning, and improving data analytics.

Improvement in these areas also requires key observational capabilities such as surface weather stations, weather balloons and aircraft, radar and satellites, targeted field studies and novel innova-

tive methods such as webcams and crowd-sourced observations, which can be especially valuable in remote or rural areas.

In the coming decade, there are likely to be new satellite capabilities based on the recommendations of the National Academy of Sciences' Earth Science Decadal Survey, which I have the privilege of co-chairing. If the high priority recommendations put forth in the report are implemented, particularly those related to clouds, precipitation, aerosols, winds, ice, and other phenomenon, the observational information to inform the physics and meteorological and climate modeling will tremendous.

Another critical area of advancement is in the social sciences because the full value of our weather and climate forecasting capabilities and risk assessments can only be realized when they are used and understood by people beyond the community, people other than the experts. And these kinds of capabilities could never be realized without Federal investments in both the research and operational domains. The returns on these investments in both dollars and capabilities are tremendous, and because much of this investment flows through universities, it supports the development and training of a capable workforce that will contribute to the strength, health, and safety of our Nation in the future.

Another area in which CIRES is very active is in the development and implementation of the National Integrated Drought Information System, or NIDIS. NIDIS coordinates and integrates drought research from various sources, and drought will be a key manifestation of climate change. Drawing from existing capacity in states and universities and across Federal agencies, NIDIS works to improve the nation's capacity to manage drought-related risks by providing the best information available and tools to assess potential impacts of drought and to support drought preparedness. Their improved drought forecasting and monitoring provides the kind of objective and timely information that farmers, water managers, decisionmakers, and State and local governments need for effective drought risk management and response, none of which would be possible without the Federal investment and structure provided through NIDIS.

Finally, these weather and drought processes I am referring to occur against an evolving backdrop, which as Senator Gardner mentioned, is climate change. Climate change has implications for weather, seasonal climate, drought, air quality, sea levels, storm surge, human health, and many other aspects of our environment that affect the way we live.

Our success as a society really in the face of climate change is going to depend on four things: the magnitude of those changes, the rate at which they occur, our ability to anticipate them, and how well equipped we are to deal with them. It is critical that we invest in and use our understanding of the physical, chemical, ecological, and social dimensions of the earth system to understand these issues and best position us for success in the future.

Thank you, Mr. Chairman, Ranking Member Baldwin. I appreciate your invitation to testify before this important committee, and I look forward to the Committee's questions.

[The prepared statement of Dr. Abdalati follows:]

PREPARED STATEMENT OF DR. WALEED ABDALATI, DIRECTOR,
COOPERATIVE INSTITUTE FOR RESEARCH IN ENVIRONMENTAL SCIENCES,
UNIVERSITY OF COLORADO BOULDER

Thank you, Chairman Gardner and Ranking Member Baldwin and the other distinguished members of the committee, for holding this important hearing today, and for allowing me to provide testimony. It is an honor to be here today to speak about the state and importance of such critical environmental matters as weather forecasting, drought management, and related issues. I thank this committee for its efforts to equip the Nation to face challenges of human and economic importance through advancing atmospheric research in ways that have improved weather forecasting, our understanding of air quality, and our ability to understand and deal with drought. Investments by the Federal government in research in these and related areas are critical to positioning individuals and the Nation to successfully meet the challenges posed by varying weather and climate conditions with which our economy, livelihood, and prosperity are so intertwined.

From the earliest days of civilized society, people have sought to understand the world around them and the conditions in which they live in order to be successful in the face of challenges, and to capitalize on opportunities presented. In few places is the value of such understanding more immediately evident in than in the areas of weather and drought, which is why I am happy to be here to discuss the current state of knowledge, the value of that knowledge, and ways in which that knowledge can be improved.

I am the director of the Cooperative Institute for Research in Environmental Sciences (CIRES) at the University of Colorado Boulder. CIRES is NOAA's largest cooperative institute, and we support the agency in the execution of its mission and carry out a wide range of research aimed at understanding many aspects of the Earth's environment—from the surface of the Sun to the depths of the Earth's interior. A key part of our mission is directly supporting NOAA in its weather forecasting efforts, developing key insights into atmospheric phenomena, and building modeling and analytical tools to improve forecasts. Another area in which we are very active is in the development and implementation of the National Integrated Drought Information System (NIDIS), which seeks to "Advanc[e] drought science and preparedness across the nation" (*https://www.drought.gov/drought/*).

I would like to focus my initial comments on weather forecasting and improvement, then provide some perspectives on NIDIS, and finally speak a little bit about the broader backdrop against which these key societally critical activities lie.

Weather Forecasting and Improvement

In the last five years forecast model improvements made by NOAA researchers and their colleagues (through partnerships such as the cooperative agreements with CIRES and our sister institute, the Cooperative Institute for Research in the Atmosphere [CIRA], based in Fort Collins at Colorado State University, as well as grants to other researchers) have meant we are doing a significantly better job forecasting thunderstorms, blizzards, floods, and even smoke from wildfires. One measure of forecast error, Root Mean Square Error (RMSE)—or the difference between what was observed and what was predicted—is down 25 percent in last 5 years alone, and we find even greater improvement in some areas. Our skill in pinpointing the location of precipitation in, for example, has improved by 50 percent in the last 5 years.

However, limits in prediction capability and the lag from research to operations can come at a high cost. As a tragic example, in 2013, the HRRR model (High-Resolution Rapid Refresh) estimated strong thunderstorm winds would reach a Yarnell, Arizona wildfire site. The model, however, was still in development, it was not yet operational, so this information was not yet incorporated in weather forecasting offices. Tragically, on June 30th, nineteen City of Prescott firefighters, members of the Granite Mountain Hotshots, were trapped and killed when the wind-shift left them with no escape. The experimental new model had forecast that wind shift with great accuracy. Three years later, when HRRR was operational, the National Weather Service in San Francisco, CA was able to use the model to tell the public where wildfire smoke was expected to spread, serving the health and safety needs of the community. And in 2018, during the Carr fire in California, detailed smoke forecasts allowed Amtrak to make informed decisions about suspending some regional services until visibility improved. The HRRR smoke model is used widely today, including by TV broadcasters to tell viewers what to expect, when, and where. An informed public facilitates the realization of these benefits, which are health-related, safety-related, and economic in nature.

These detailed benefits and capabilities go far beyond smoke and the rain and temperatures that we typically associate with weather. They are also tied to hail, for example. An experimental version of the HRRR ensemble regional analysis and prediction system forecasted the location and path of a severe hail storm eight hours in advance of hitting Colorado Springs last August (2018). In addition, HRRR accurately predicted the maximum amount of snowfall from a 2018 snowstorm in the Midwest with 36 hours of lead time. There are other critical forecasting tasks the Nation relies on, which I will mention briefly here: We at CIRES support NOAA and other agency efforts to understand and forecast air quality, for example, both during high impact events, like wildfires or a massive oil spill, and during normal pollution seasons like summer in Denver or winter in Salt Lake City. We conduct world-class atmospheric chemistry research essential to these weather modeling efforts, and we focus on the world's frozen places, too. Changes in Earth's ice cover impacts weather and climate, in ways we don't entirely understand yet, and they have direct, immediate implications for military and commercial work in the Arctic. Ship captains and navigators need to know where the sea ice is, and where it will be tomorrow. These kinds of information protect and save lives and property, allowing individuals, businesses, governments and others to make informed decisions that impact their well-being, livelihood, and prosperity.

Despite these successes, there remain critical needs for more accurate forecasts, better lead times, and information at more local levels. To achieve these objectives, we need continued improvements in high-performance-computing as well as sustained and improved observations. In the area of computing, there is a significant need for support of the development, maintenance, and operation of supercomputers, as well as the effective use of cloud computing as a high-performance computing resource. Beyond the hardware/computing, however, there is a critical need for support for research on techniques, such as improving weather model code, advancing machine learning, and improving data analytics.

On the observational side, quality data really are foundational to the ability to successfully understand and predict weather. Key observation capabilities include surface weather stations, weather balloons and aircraft observations, radars and satellite observations of atmospheric, oceanic, and land-surface phenomena, targeted field studies, and novel innovative methods such as web cams and citizen science/crowd-sourced observations. These crowd-sourced observations can be especially critical in remote or rural areas.

In the area of ground-based observations, the Mesonet network in Oklahoma, with its 120 ground stations covering the state, serves as an excellent example that could be emulated elsewhere. In the case of citizen science, the Community Collaborative Rain, Hail, and Snow (CoCoRaHS) system, developed by Professor Nolan Doesken at Colorado State University after the devastating 2013 floods in Colorado, allows citizens to collect local rain, hail, and snow, data all over the country, upload it to a central database, and facilitate improved local-scale weather forecasting. This kind of citizen science, which costs the government almost nothing, provides detailed local information for improved precipitation forecasts that would otherwise be nearly impossible to achieve.

In addition to computational, analytical, and observational capabilities, continued cross-line office partnerships between the National Weather Service (NWS) and the Office of Atmospheric Research (OAR) are essential in order to coordinate the innovative weather services needed to address future challenges, as well as to facilitate the transition of scientific advances into operations and applications.

Fortunately, there are some significant developments underway or on the horizon to advance our capabilities in the understanding and prediction of weather. One is the Unified Forecast System (UFS). UFS is NOAA's community-based, coupled comprehensive Earth system modeling system, designed to support the Weather Enterprise and to be the source system for NOAA's operational numerical weather prediction applications, as well as to serve both the research and development and operational communities engaged in the numerical prediction of the Earth System. Using advanced high-performance computing architectures, the system will incorporate the most recent advances in weather prediction modeling from NOAA and the research community. UFS is expected to:

- Implement a weather-scale, fully-coupled Numerical Weather Prediction System
- Extend forecast skill beyond 8 to 10 days
- Improve hurricane track and intensity forecast
- Extend weather forecasting to 30 days.

Elsewhere on the modeling and physics front is the FV3, the Finite Volume Cubed-Sphere Dynamical Core, under development at NOAA's Geophysical Fluid

Dynamics Laboratory, which incorporates state-of-the-art physics in new ways, allowing for more accurate global forecasts. FV3 is currently being implemented into NOAA's Global Forecast System (GFS) at the National Centers for Environmental Prediction (NCEP) and is expected to be fully operational for global forecasts later this year. NOAA's academic partners played key roles in evaluating this and other core model packages under consideration and determining which would best serve the Nation's growing forecasting needs. Other applications, such as regional high-resolution forecasting and coupled atmosphere-ocean modeling for seasonal prediction, are planned for later implementation at NCEP. These new capabilities, coupled with more robust ensemble model forecasts in which multiple models are run and compared to reduce uncertainty, will continue to advance our capabilities in weather prediction accuracy and reliability.

Another major effort that will accelerate knowledge and capabilities is the Earth Prediction Innovation Center (EPIC), which was authorized under the recent NIDIS and Weather Research and Forecast Innovation Act Reauthorizations. This integration of efforts by NOAA and the National Center for Atmospheric Research is expected to advance numerical guidance skill, reclaim and maintain international leadership in numerical weather prediction, and improve the research to operations transition process. It expected that EPIC will:

- Leverage the weather enterprise
- Enable scientists and engineers to collaborate more effectively
- Strengthen NOAA's ability to undertake research projects
- Leverage existing resources in NOAA
- Create a community global weather research modeling system accessible by the public
- Be computationally flexible
- Utilize cost-effective, innovative strategies and methods, including cloud-based computing capabilities, for hosting and management of part or all of the system.

In addition to modeling, there are likely to be new satellite capabilities on the horizon, based on the recommendations of the National Academy of Science's Earth Science and Applications from Space—2017 decadal survey, which I had the privilege of co-chairing. If the high-priority recommendations put forth in that report are implemented, particularly those related to clouds, convection, and precipitation, as well as aerosols and winds, the observational information to inform the physics of meteorological and climate modeling will be tremendous.

Another critical area of advancement that continues to be recognized is in the area of social science. The successful use of the information generated depends on it being delivered in a way that people respond to and use, and also that risk is communicated effectively. Risk communication was specifically called out in the Weather Research and Forecasting Innovation Act of 2017 The true value of our weather forecasting capabilities can only be realized when they are used and understood broadly. For this reason, the social science dimension of weather forecasting is critical to the broader enterprise.

And finally, these advances that I described above and future capabilities could never be realized without Federal investments in both the research and operational domains. This research is carried out by Federal scientists, not just at NOAA, but at NASA, the Department of Energy, and elsewhere; as well as by university scientists, including those at CIRES, who are supported by Federal dollars. The return on those investments in research our government makes nationally is tremendous. Though somewhat dated, a 2009 study from the National Center for Atmospheric Research, in Boulder, Colorado, showed Americans used 300 billion weather forecasts annually at an estimated the value of $31.5 billion. At the time, the funds spent on such forecasts totaled roughly $5 billion annually, providing an enormous return on investment. No doubt, in the ten years since, weather forecast usage and economic benefit have increased considerably. Beyond the dollars, however, a critical benefit realized by these Federal investments and the broader weather enterprise has been the training of students, who will serve as the next generation of forecasters, scientists, entrepreneurs, and weather savvy citizens and professionals. Because much of the investment flows through universities, where training and education are fundamental to our mission, the investment of Federal dollars today ensures the development of a capable workforce and comprises a sound and important investment in the strength, health, and safety of our Nation in the future.

National Integrated Drought Information System (NIDIS)

I would like to turn our attention now to the National integrated Drought Information System, or NIDIS. NIDIS was authorized by Congress in 2006 and reauthor-

ized in 2014 and 2019 to coordinate and integrate drought research, building upon existing federal, tribal, state, and local partnerships in support of creating a national drought early warning information system. NIDIS aims to improve the Nation's capacity to manage drought-related risks by providing the best available information and tools to assess the potential impacts of drought, and to prepare for and mitigate the effects of drought. CIRES supports NIDIS through the seven CIRES/CU Boulder staff members who comprise the NIDIS Program Office, based at NOAA's Earth System Research Laboratory in Boulder, CO.

A major focus of NIDIS this year is development of a national *drought early warning system.* In support of that development, NIDIS is:

- Partnering with private sector, academic institutions, agencies and citizen scientists
- Hosting the National Drought Forum in Washington, DC, July 30–31, which seeks to educate the community on the status of droughts in the US, examine needs, report progress on the early warning system, etc.
- Developing a national coordinated soil moisture monitoring network (multi-agency, multi-institutional)
- Developing a public health strategy to support research and communications of the links between drought and public health impacts (There will be a summit in Atlanta in mid June on this topic.)
- Studying the Mississippi River corridor and its sensitivity to drought, including impacts to agriculture, navigation and transportation, manufacturing, recreation and tourism
- Conducting a Southwest regional drought economic impact assessment to compare the scope and severity of the 2017–2018 drought to previous ones to understand how conditions influenced economic, health and even crime outcomes
- Implementing a drought and wildland fire strategic plan, to improve the use of drought information in wildland fire management for ecological health, public health, and firefighter safety.

Government investment has been critical to NIDIS. Reauthorization in 2019 recommended an increase in funding from $13.5 million in Fiscal Year 2019 to $14.5 million in Fiscal Year 2023. NIDIS supports an integrated, collaborative approach to managing drought events, building on existing programs and partnerships. This approach includes improved drought forecasting and monitoring that provides the kind of objective and timely information that farmers, water managers, decision-makers, and state and local governments need for effective drought risk management and response. By drawing from existing capacity in states, universities, and across Federal agencies, NIDIS serves as a model for federal-state collaboration in shared information services, none of which would be possible without the Federal investment and structure provided through NIDIS.

Backdrop and Context

As the scientific community works to understand atmospheric and oceanic processes that determine and influence weather, it is critical to understand that these processes occur against an evolving backdrop, which is climate change. As heat continues to be trapped in the atmosphere and temperatures rise, there is an increase in the amount of energy in the system that ultimately has implications for weather, climate, drought, air quality, sea level, storm-surges, human health, and many other aspects of our environment that affect the way we live. It is that same type of understanding of basic physics that we use to develop reliable weather forecasts that informs our understanding of climate change and the implications for the Earth system. The effects and manifestation of climate change are well documented and well understood, not just by the scientific community, but by entities with a vested interest in such knowledge. These include the U.S. military, the insurance industry, the real-estate industry, coastal planners, farmers, etc.

Unfortunately, the climate change discussion has been far too politicized in recent years, in large part because the stakes are very high on multiple fronts (strategic, economic, social, etc.). Paradoxically, it is precisely because those stakes are so high that the conversation needs to be depoliticized, and that the leaders of this Nation and the leaders of the world accurately incorporate our best understanding of climate change in policy-and decision-making. As a scientist, I focus on the underlying physics of change and the mechanisms, but I am also well aware that there are economic implications of policies that go far beyond the physics of climate change. It is for that reason, that I am not trying today to prescribe solutions to the climate challenges. Rather I am here simply to ask that as policies are made that intend to support economic prosperity now and in the future, the role climate change plays

in that future be considered in a way that takes advantage of what we know today, and ensures we continue to build on that understanding in the future, and that a flow of that information can be used for strategic and informed decision-making.

The Earth's climate is changing. It always has, and it always will. Our success as a nation and society depends critically on:

- The magnitude of those changes
- The rate at which they occur
- Our ability to anticipate them
- How well equipped we are to deal with them.

The first two items are dependent on whatever mitigative measures are taken, since mitigative measures can limit the magnitude of the change and slow them down. The third bullet is why the research community is working to understand the changes that are occurring, the mechanisms that underlie those changes, and what those changes mean for the future. The final bullet speaks to our resilience, which requires awareness and the effective use of information, as well as a robust flow between the knowledge producers and the knowledge users (decision makers, planners, etc.).

So as we discuss weather and drought today, it is critical that we keep in mind that the phenomena we seek to understand—for the purpose of saving lives and property and securing economic prosperity—are occurring against a backdrop that is changing. It is changing in ways that follow similar physics and have major implications for those shorter-term weather-and drought-related phenomena. Investments in research are critical to our ability as a Nation and as a society to manage the challenges associated with a changing climate, to capitalize on the opportunities created, and ultimately, to ensure that we use our knowledge and understanding of the physical, chemical, ecological, and social dimensions of the Earth system to best position us for success in the future.

Thank you, Mr. Chairman, Ranking Member Baldwin, I appreciate your invitation to testify before this important committee, and I look forward to the committee's questions.

Senator GARDNER. Thank you very much for your testimony.

Dr. Bronk, please proceed.

STATEMENT OF DEBORAH A. BRONK, PH.D., PRESIDENT AND CHIEF EXECUTIVE OFFICER, BIGELOW LABORATORY FOR OCEAN SCIENCES

Dr. BRONK. Thank you for the opportunity to provide this testimony in service to this country and the ocean, both of which I love.

I am an oceanographer who has done research in over 50 research expeditions all around the world. I have been the president and chair of two scientific societies that represent over a million scientists in the U.S. I served as Director of the Division of Ocean Sciences at the National Science Foundation, and I currently serve as President and CEO of one of the world's most innovative oceanographic institutions, the Bigelow Laboratory for Ocean Sciences.

I am about as middle of the road politically as one can get, which means I am constantly defending one side or the other. I have what I would love to see more of in this country.

On this panel, I represent the ocean science community and their need to provide the data necessary for accurate climate predictions. My take-home message is this. With the large increase in greenhouse gases in our atmosphere, we are conducting a massive experiment on the only planet we have. To know how best to protect ourselves from and respond to the changes in our climate, the United States should commit to sustained increased investment in four things: climate modeling; collecting the global ocean observations of key physical variables, including atmospheric aerosols above the ocean; developing the tools needed to generate global observations

of key chemical and biological parameters; and training and attracting the workforce needed to do all three of these things successfully.

I emphasize the word "sustained" because programs that can lay out work plans over the course of a decade will be better able to leverage resources and save the taxpayers money.

Finally, the priorities should be generated by leaders in their respective scientific disciplines and should be done in the context of a robust international collaboration.

Now to the science. Every year humanity releases billions of tons of carbon into the atmosphere and as a result, our oceans are warmer. Ocean warming leads to the melting of sea ice, a reality I have seen in my own work in the Arctic. Ocean warming leads to sea level rise and coastal flooding, a reality I saw firsthand living near Norfolk, Virginia, home of the U.S. naval fleet. Ocean warming leads to changes in the migration and distribution of marine organisms, changes that have threatened disruption of the $200 billion fishing sector in the U.S. Ocean warming also leads to the reduction in ocean oxygen, which impacts more than 500 ecosystems all around the world, including the tragic dead zone where the Mississippi River enters the Gulf of Mexico.

Then there is ocean acidification. When carbon dioxide in the atmosphere dissolves in seawater, it changes ocean chemistry and threatens many organisms, including coral reefs, the loss of which is estimated to cost this country $140 billion by the end of the century.

To prepare and mitigate these changes, we need to know what we will be facing, and that requires accurate predictive climate models. At a basic level within a climate model, the surface of the earth is divided into squares and each square includes a series of mathematical equations that represents the important processes that occur. For a model to accurately represent what is happening in the real world it must have data and lots of it. Currently there is not nearly enough data from the ocean.

From an ocean perspective, climate models—most need data on three cycles: heat, fresh water, and carbon. A heat budget measures the balance between the incoming solar radiation and the outgoing heat that escapes. The fresh water budget is important to understand in the salinity or salt in the ocean, which along with temperature, determines the density of water and so controls the deep global ocean circulation. The ocean carbon cycle is made up of many pools of carbon such as carbon dioxide or organisms and the processes that move this carbon from the atmosphere to the ocean and the sediments below. This cycle is by far the most complex and the one with the largest uncertainty in climate models.

To collect the data we need requires a whole suite of measurements, including unmanned instruments like buoys and gliders, as well as shipboard measurements. Unmanned approaches, cost effective, exist for many physical and chemical variables such as temperature and salinity and pH, but there are many chemical and biological measurements where unmanned methods and instrumentations simply do not exist, which is what severely limits our ability to collect the data we need and strongly impedes our understanding of the earth's climate system.

The ocean does not see national boundaries, so expanding a truly global ocean observation system requires strong international cooperation. And developing and conducting these ocean observations will require a trained work force, which is another reason the U.S. should increase its investment in STEM education now. I also want the best and the brightest from around the world to be on Team USA in this effort. We should welcome students from every country around the world, train them well, and then staple a green card to their Ph.D. diploma, and hope that they stay with us.

Thank you for taking up this issue, and thank you for giving me the opportunity to share my views.

[The prepared statement of Dr. Bronk follows:]

PREPARED STATEMENT OF DEBORAH A. BRONK, PH.D., PRESIDENT AND CHIEF EXECUTIVE OFFICER, BIGELOW LABORATORY FOR OCEAN SCIENCES

MY BACKGROUND

For the last thirty years I have devoted my life to the study of the oceans. For twenty-six of those years I was a college professor who ran my own laboratory focused on the study of nutrients and how they control the growth of phytoplankton and bacteria at the base of the ocean food web. I have participated in over 50 research expeditions from the Arctic to the Antarctic. Over the last decade, I have also taken what I learned in the ocean, and applied it to help water reclamation facilities.

Throughout my career I have been committed to service—to science and this country. I was a member of the Ocean Carbon and Biogeochemistry Scientific Steering Committee and the U.S. Carbon Cycle Science Plan Working Group, and have served on numerous review committees for tenure and promotion, research funding, and programs, including as chair of the institutional review of the Woods Hole Oceanographic Institution.

I was elected member-at-large and then president of the Association for the Sciences of Limnology and Oceanography, the largest international scientific society dedicated to the aquatic sciences. I have also served as member-at-large, treasurer and chair of the Council of Scientific Society Presidents, an organization that represents over a million scientists in the U.S. across all scientific disciplines.

From 2012 to 2015, I served at the National Science Foundation as section head and then director of the Division of Ocean Sciences where I was responsible for programs across all ocean disciplines as well as major oceanographic facilities including NSF use of the U.S. research fleet, ocean observing, and the ocean drilling program. It is an honor to continue that service by providing testimony to this committee. I offer these thoughts as a citizen based on my experience as a scientist, an educator, and a mother.

I also note that I am a middle child; we tend to be the peacekeepers. I was raised by very conservative parents that I respected and adored and I have spent my life working with many very liberal individuals who are like a second family. This means I have spent my entire life trying to look at both sides of what can be very contentious issues. When it comes to the ocean there are many.

INTRODUCTION

In my comments, I will focus on climate, which is the average weather conditions on the planet over decades. This is in contrast to weather, which is the day to day state of the atmosphere and how it changes over days to weeks. One way to think about this is that climate is what you expect, but weather is what you get on any given day.

My take home message is that the United States should commit to a sustained investment in four things—climate modeling, collecting the global ocean observations of key physical variables, developing the tools needed to generate global observations of key chemical and biological parameters, and training the workforce needed to do all three successfully.

There is an abundance of scientific literature on the ocean's impact on climate and I will not do it justice here. In the time and space allowed I have tried to provide a brief tutorial of the basics that I would want all of our elected officials to know. I direct interested readers to a number of summary reports including Sustaining

Ocean Observations to Understand Future Changes in Earth's Climate (National Academies 2017), the National Climate Assessments (Jewett and Ramanou 2017; Taylor *et al.,* 2017; Hayhoe *et al.,* 2018; Pershing *et al.,* 2018), the State of the Carbon Cycle Reports (USGCRP 2018), and the many products developed through the Intergovernmental Panel on Climate Change (IPCC).

A. Why the climate is changing

Life exists on Earth because the planet has a blanket of atmospheric gases, including water vapor, carbon dioxide, and methane, that acts like the glass of a greenhouse and retains some of the energy from incoming solar radiation. Over the past 100 years, mankind has taken carbon buried deep within the ground as fossil fuels, and burned it to power the incredible technological advances started during the Industrial Revolution. The result raised the standard of living for billions of people around the globe. It also increased the concentration of these greenhouse gases in our atmosphere resulting in an average increase in global temperature from 1901 to 2016 of ~1.0°C (1.8°F; Hayhoe *et al.,* 2018).

This massive alteration of Earth's atmosphere has had a profound impact on our oceans, which have absorbed more than a quarter of the carbon dioxide released. Here I highlight two direct effects this increase in greenhouse gas concentrations have had on our oceans—they are now warmer and the pH of the water has declined, making the ocean more acidic. Both of these changes have had an effect on the ocean's role in climate.

B. Ocean warming

Every year, humans release about 10 gigatons (36 billion tons) of carbon into the atmosphere from burning fossil fuels and other activities (Le Quéré *et al.,* 2018). In 2016, atmospheric levels of carbon dioxide passed 400 ppm, a striking milestone and a dramatic increase from pre-Industrial levels of 280 ppm. This huge surge in the levels of carbon and other greenhouse gases blanketing the atmosphere traps excess heat in the Earth's climate system.

The oceans have absorbed 93 percent of this excess heat and store it for two main reasons. First, water has the highest specific heat capacity of any common material, meaning that it can absorb a great deal of heat before its temperature actually increases. Second, the global ocean is vast, covering 71 percent of the Earth's surface with an average depth of 4 kilometers (12,123 feet). This incredible volume makes it a huge reservoir for heat that is continuously distributed by currents and other circulation processes.

The highest degree of warming has taken place in the upper 75 meters (246 feet), as this upper layer lies closest to the warming atmosphere. Average global temperatures in the surface ocean have increased by 0.7 ± 0.08 °C (1.3° ± 0.1°F) per century between 1900 and 2016 (Jewett and Romanou 2017). The upper ocean also mixes vigorously, distributing the heat it absorbs. As more energy enters Earth's climate system, heat penetrates deeper into the ocean. Warming at the poles is especially impactful because these are the sites of deep ocean water formation. The combination of ice formation and extreme cold makes the waters in the North Atlantic dense relative to surrounding waters. These dense waters sink carrying heat to the ocean's interior.

Most of the remaining 7 percent of this heat goes into melting sea ice, glaciers, ice caps, and warming the continent's land mass. Only a tiny fraction goes into warming the atmosphere, but even that is felt in rising global temperatures. The six warmest years on record have all occurred since 2010 (NOAA State of the Climate Report 2019). While there is much debate over the record of increasing air temperatures, the ocean does not have parking lots or heat island effects and yet still we see significant increases in temperature.

The complex interactions between continued greenhouse gas emissions, the resulting energy imbalance, and changes in ocean heat storage and transport will largely control the impacts of anthropogenic climate change. I focus on five critical impacts here—melting of sea ice, sea level rise and coastal flooding, changes in the distribution and migration of marine organisms, the decline of coral reefs and deoxygenation of the ocean.

1. Melting of sea ice

The Arctic Ocean is important to the world's ecology, climate, and economy. Due to the shape of the planet, more incoming solar radiation concentrates at the equator than at the poles. The atmosphere and ocean currents address this energy imbalance by transporting heat away from the equator. This process has driven annual average temperatures in the Arctic to increase more than twice as fast as the global average, resulting in substantial loss of sea ice and glacial mass. Climate models

using the IPCC "business as usual" scenario predict average Arctic temperatures will increase 7°C (45°F) by the year 2100.

Since 1979, the annual average extent of Arctic sea ice has decreased 3.5 to 4.1 percent per decade, including an 80 percent loss in summer sea ice volume (Comiso and Hall 2014; Vaughan *et al.,* 2013). The melting of sea ice now starts 15 days earlier than it did in the past, and it is predicted that the Arctic will be nearly free of late-summer sea ice by the middle of this century (Taylor *et al.,* 2017).

The lack of summer Arctic sea ice is increasing seaside erosion, undercutting villages, and washing away infrastructure. Alaskans are being forced to change their hunting strategies and even the locations of whole communities. From 2010 to 2017, I made seven trips to Barrow, Alaska, the northern most village in the U.S. In that short time, the changes to the region and community have been profound including the impending destruction of the main road from Barrow to Point Barrow due to erosion from the sea.

The effect of sea ice loss is profound because it is a key part of polar ecosystems. Large blooms of algae occur at the ice edge and form the base of the Arctic Ocean food web (Arrigo 2014). As ice coverage declines, the timing and location of the ice edge blooms change, as does critical habitat for more than a thousand species, including polar bears, seabirds, and seals. Many organisms hunt, give birth, migrate and shelter on ice, and the loss of ice is causing declines in a number of species (Laidre *et al.,* 2015). As one example, walruses are moving farther from shore as the sea ice extent shrinks, and hunters from native Arctic communities that rely on them must now travel further across open water, threatening both people's safety and traditional ways of life.

Shrinking ice cover is also making the Arctic more accessible to shipping, with access by various countries and commercial entities. This brings both new opportunities and risks. The challenges that accompany greater access include protecting the border from new threats to national security, a heightened threat of oil spills and illegal fishing, and the need to update severely outdated nautical charts and put search and rescue plans in place.

2. Sea level rise and coastal flooding

Sea level is rising as a result of warming ocean temperatures and the melting of ice on land, such as glaciers and ice sheets. Warming water temperatures contribute to sea level rise because of thermal expansion—warm water takes up more volume than cooler water. Since 1900, average sea level has risen by about 16 to 21 cm (7 to 8 inches) globally with about a third of the increase due to thermal expansion. Even more alarming than the amount is that nearly half of this increase has occurred since 1993. Sea level continues to rise at a rate of about one-eighth of an inch per year (Hayhoe *et al.,* 2018).

The ultimate magnitude of sea level rise will vary based on how land ice responds to continued warming. Predictions for the century between 2000 and 2100 vary from one to four feet of sea level increase, with extreme increases of over eight feet if the Antarctic ice sheets collapse. If the ice sheet on Greenland were to melt, sea level could increase by an incredible 21 feet. These scenarios are unlikely, but I note that past increases have been larger and occurred more rapidly than expected. As a nation, we need to prepare for the worst.

There will be many consequences of higher sea levels. Destructive and deadly storm surges will reach farther inland, bringing more frequent flooding with high tides. These floods are disruptive and expensive. Today, nuisance flooding is estimated to be from 300 percent to 900 percent more frequent within U.S. coastal communities than 50 years ago (Sweet *et al.,* 2014).

As ocean and atmospheric warming trends persist, sea level rise over the next centuries will ramp up to rates significantly higher than what we see today. Nearly 40 percent of people in the United States live in high-population-density coastal areas, where they will be subject to the flooding, shoreline erosion, and hazardous storms that come with rising sea levels. These impacts will also be felt globally—eight of the 10 largest cities in the world are near a coast as are four of the 10 largest cities in the U.S.

Specific locations will experience sea level rise differently based on local factors, such as subsidence and rebounding from natural geological processes, changes in regional ocean currents, and withdrawal of groundwater and fossil fuels. Sea level rise has already increased the frequency of flooding at high tide by a factor of 5 to 10 since the 1960s for several U.S. coastal communities. The frequency and extent of tidal flooding are expected to continue to increase in the future and its anticipated that there will be more severe flooding associated with coastal storms, hurricanes and nor'easters (Sweet *et al.,* 2014). The infrastructure essential for local and re-

gional industries in urban environments will be threatened, including roads, bridges, oil and gas wells, and power plants.

3. Changes in the migration and distribution of marine organisms

Increases in water temperatures and its associated effects have caused alterations to global patterns of ocean and atmospheric circulation, precipitation, and nutrients. Collectively, these effects are having a drastic impact on the abundance, diversity, and distribution of marine organisms—from the smallest bacteria to the largest fish.

Most of the life in the ocean is microscopic. While we cannot see these microorganisms without a microscopic, they produce half of the oxygen we breathe and form the base of ocean food webs. As most are single-celled organisms that can only drift in the water column, these vital plankton are highly vulnerable to ocean changes.

Broadly speaking, the ocean has two parts—a warmer, less dense layer at the surface that receives sunlight but has low nutrients (because the microorganisms have taken them all up) and a deep layer that is denser and colder, with no light but lots of nutrients (because decomposing organisms sink and release nutrients as they decompose). Rapid warming of surface water is increasing the temperature difference between these layers, increasing the stratification of the ocean and preventing the surface and deep water from mixing efficiently. As a result, most phytoplankton have a harder time staying near the sunlight that they need to grow, and the greater stratification restricts the delivery of nutrients phytoplankton need from the deep ocean.

These changes to the base of the ocean food web reverberate through other marine species including the fishing sector, which contributes over $200 billion in economic activity each year and supports 1.6 million jobs (NOAA Fisheries 2017). The species this industry relies upon are changing as a result of warming waters. These shifts in species distributions are complicating fishery management by changing the nature of traditional fisheries and efforts to protect endangered species.

These shifts are especially prominent off the U.S. east coast. For example, surveys conducted by state and Federal agencies documented a number of shifts in distribution in fish, shellfish and other species along the mid-Atlantic with a trend toward poleward movement and/or movement to deeper cooler water (Lucey and Nye 2010). Recent research at Bigelow Laboratory shows that copepods (tiny crustacean that eat phytoplankton and are then eaten by higher organisms) are less viable if grown in warmer waters. Shrinking copepod populations will threaten numerous marine species that rely on them for nutrition, including the endangered North Atlantic right whale (Record *et al.,* 2019).

I have provided a few examples of shifts in the distribution of organisms but I note that detecting and quantifying these changes are a challenge because each species within a community may response differently due to differences in their life history, where they live, and what they eat. Organisms also vary with respect to the outside forces that affect them such as fishing, destruction of their habitat or pollution. Due to this complexity, detecting and understanding shifts in species and populations requires a commitment to long-term monitoring programs, which have historically been very difficult to maintain.

4. Coral reef decline

Coral reefs are the foundations of many tropical ecosystems. Temperature is a powerful controlling variable for the health and location of coral reefs, and many exist at or near their upper temperature limit (Schoepf *et al.,* 2015). As a result, ocean warming has had a devastating effect on coral reefs around the world. When corals are exposed to waters even slightly above their temperature maximum, they can release the symbiotic algae, called zooxanthellae, that live within their tissues. This process is known as bleaching because of the stark white color it turns corals. The symbiotic algae provide vital nutrients to the coral, and so bleaching often kills them.

During the last 30 years, there have been several global-scale coral bleaching events (in 1987, 1998, 2005, and 2015–2016) that have resulted in a dramatic reduction of live coral. This puts the entire community of plants and animals that rely on the reefs in jeopardy. In the United States, mass bleaching events and outbreaks of coral diseases have occurred in the waters off Florida, Hawaii, Puerto Rico, the U.S. Virgin Islands, and the U.S.-Affiliated Pacific Islands (Miller *et al.,* 2009; Rogers and Muller 2012).

In addition to the direct physiological stress of elevated temperatures, ocean warming also increases the incidence of coral disease, and ocean acidification affects the ability of corals to produce their calcium carbonate structures (discussed further in section B below). When these effects compromise reef-building corals, the entire reef ecosystem becomes threatened (Jones *et al.,* 2004). This includes a vast number

of invertebrates and fish, organisms that many coastal communities depend on for subsistence. Corals also provide storm protection to coastal ecosystems and can form the basis of local or regional tourism economies (Prachett *et al.,* 2008).

5. Low oxygen

Oxygen makes up 21 percent of the air we breathe and supports life on Earth, and half of this oxygen was produced by phytoplankton in the ocean. In water, oxygen exists in a dissolved form and acts as a limiting resource that controls the growth of many marine species. One consequence of climate change is the loss of oxygen from the oceans, known as ocean deoxygenation (Deutsch et al 2011).

Levels of oxygen in the ocean depend on a balance between oxygen production through phytoplankton photosynthesis, depletion through respiration by animals, and physical mixing processes. Climate change is shifting this balance in several ways. At the most fundamental level, warmer water holds less oxygen than cold. As the oceans warm, they lose their ability to physically hold oxygen. The same holds true for greenhouse gases like carbon dioxide and methane.

In addition, the surface ocean is warming fastest due to its proximity to the atmosphere. This makes the surface water less dense and less able to mix with the colder, denser water below, limiting the distribution of oxygen. At the same time, global ocean circulation patterns are shifting with climate change. Slower circulation and more upwelling of oxygen-poor deep water are further decreasing oxygen levels in the ocean.

Long-term monitoring efforts reveal that oxygen concentrations have declined during the 20th century, and the IPCC 5th Assessment Report predicts that they will decrease 3–6 percent during the 21st century due to ocean surface warming. In coastal regions, low oxygen is a particularly devastating problem and dead zones where most organisms cannot live because of insufficient oxygen have been reported for more than 479 systems and their numbers have doubled every decade since the 1960s (Diaz and Rosenberg 2008).

Changes to biological processes are also contributing to this issue. Warmer water temperatures increase oxygen demand from organisms, leading to the faster depletion of available oxygen and threats to a vast range of species, including those that comprise valuable fisheries. For example, off the coast of California, waters between 200 and 300 meters have lost 20–30 percent of their oxygen in the last 25 years (Bograd *et al.,* 2008), threatening important fisheries. In the tropical Atlantic Ocean, the vertical habitat of tuna and blue marlin reduced by 15 percent between 1960 and 2010 due to expanding oxygen minimum zones (Stramma *et al.,* 2012; Schmitko *et al.,* 2017).

C. Ocean acidification

In addition to warming, excess carbon dioxide in the atmosphere has a direct and independent effect on the chemistry of the ocean, which can also impact future climate. Ocean acidification is the process of carbon dioxide being absorbed by the oceans and causing significant changes to seawater chemistry. Global chemical processes keep gasses in the ocean and the atmosphere in equilibrium. While humans have drastically increased the amount of carbon dioxide in the atmosphere, the ocean has been working to keep up. About a quarter of the carbon dioxide we generate through industrial activity ends up in the ocean, and the resulting change in chemistry has caused the surface ocean to become 30 percent more acidic. This has occurred at a rate at least 10 times faster than any natural acidification event in the past, and affects everything from chemical processes to sea life.

When carbon dioxide in the atmosphere dissolves in seawater, it changes three aspects of ocean chemistry. First, it increases levels of dissolved carbon dioxide and bicarbonate ions, which are the fuel for photosynthesis in phytoplankton and plants. Second, it increases the concentration of free hydrogen ions, which makes the water more acidic. Third, it reduces the concentration of carbonate ions. Carbonate is critical to many marine organisms, which use the mineral calcium carbonate to form their shells or skeletons. For some species, rising temperatures and decreasing oxygen levels in the ocean may exacerbate the effects of ocean acidification.

The cold temperature of high latitude ecosystems results in greater carbon dioxide solubility making polar regions highly vulnerable to ocean acidification. Sea ice loss is also causing Arctic waters to acidify faster than expected. Further, acidification along the United States coast is greater than the global average for a number of reasons, including the natural upwelling of acidic waters off the Pacific Northwest and California coasts, changes to freshwater inputs in the Gulf of Maine, and anthropogenic nutrient input into urban estuaries. Here I will focus on two major consequences of ocean acidification—changes to the ocean carbon cycle and the impact

on organisms and the industries built around them including fisheries and aquaculture.

1. Changes to the ocean carbon cycle

Carbon is recycled and reused through biological and physical ocean processes including photosynthesis, respiration by animals, and mixing within the ocean. The carbon cycle drives important biogeochemical processes that shape the character of the global ocean and planet as a whole. When organisms die, they sink, bringing the carbon that composes their bodies into the deep ocean. This is referred to as the biological pump because it pumps carbon from the surface to the deep ocean and can sequester carbon away for hundreds of years. The oceans are by far the largest carbon sink, or storage reservoir, on Earth.

The combined effect of ocean warming and acidification lowers the ability of the ocean to take up additional carbon dioxide in three general ways. First, as noted above, warmer water can simply hold less gas than colder water. Second, the warmer water in the surface ocean becomes, the more stratified the water column will be. Greater stratification reduces mixing and so reduces the ability for carbon dioxide dissolved in surface water to be mixed into deeper waters. Third, it is generally harder for organisms to build shells out of calcium carbonate in more acidic waters. This means that phytoplankton that build shells (such as coccolithophores), and are therefore heavier and so sink faster, are at a disadvantage. As the ocean continues to acidify, any selection away from organisms that build shells and towards organisms that do not, will likely weaken the biological pump and decrease the transport of carbon into the deep ocean as phytoplankton die. These effects are already being seen and the oceans are becoming less able to absorb carbon dioxide (*e.g.,* Khatiwala *et al.,* 2016).

2. Threats to organisms, including fisheries and aquaculture

The impacts of ocean acidification are diverse. Although certain species are favored by more acidic waters, ocean acidification appears to negatively impact more marine species than it helps. Organisms that use carbonate minerals to build skeletons or shells struggle with this basic function in more acidic waters. Organisms like clams, mussels, and phytoplankton that use calcium carbonate to build shells and other structures are important in environments and economies around the globe. Under the IPCC low emissions scenario, seven to 12 percent of calcifying species would be significantly affected by lowering pH, and 21 to 32 percent of calcifying species would be impacted under the high emissions scenario (Azevedo *et al.,* 2015).

Ocean acidification also appears to favor some toxic phytoplankton species that form harmful algal blooms, allowing them to become more abundant in changing ecosystems (Riebesell *et al.,* 2018). Including freshwater and marine ecosystems, harmful algal blooms are a significant environmental problem in all 50 states (EPA 2013).

Entire coral reef ecosystems are also severely threatened by ocean acidification. Corals depend on calcium carbonate to build their exoskeletons, and acidification impedes this process. The acidic water also literally dissolves coral structures, and the bulk of a coral reef itself. Many reefs around the world are dissolving faster than they can build themselves back up. In addition to forming the foundations of ecosystems, corals also provide storm protection to coastal ecosystems and can form the basis of local or regional tourism economies. By the end of this century, the loss in recreation from coral reefs in U.S. is expected to reach $140 billion (Pershing *et al.,* 2018).

Some of the animals at risk from acidification also comprise lucrative fisheries in the U.S., like lobsters in the Northeast and squid in California. These animals are physically compromised by acidification, and they may find it harder to get the food they need in acidifying oceans. Acidification impairs the senses of some fish and invertebrates, causing them to misinterpret cues from predators and engage in risky behaviors, like swimming far from home. Damage to key phytoplankton and zooplankton species can reverberate through entire food webs, affecting the fisheries that they support.

The U.S. aquaculture industry is already shifting in response to ocean acidification. Larval shellfish cannot build shells under high acidity, and high mortality rates have afflicted the Pacific Northwest's $270 million shellfish industry since 2005. The poor conditions have prompted some shellfish aquaculture facilities to relocate. In Maine, some shellfish farmers are growing kelp in an effort to improve local water quality and the health of their stocks.

D. Feedback loops between the ocean and climate

Natural systems have feedback loops that allow them to adjust to changes in the environment. In Earth's warming climate system, a positive feedback loop would increase the warming, while a negative feedback loop would reduce it. The changes in the ocean described above will affect climate in a number of different ways. Unfortunately, the feedbacks are largely positive and work to exacerbate warming.

For example, the decline in sea ice has a direct positive feedback on warming. Light colored surfaces reflect more incoming solar radiation back into space than darker surfaces. When light colored ice melts, it exposes blue ocean water. This blue ocean water absorbs more energy, thus creating a positive feedback loop. The warmer it gets, the more blue water exposed, the more solar radiation absorbed to further increase the temperature.

Ocean acidification contributes to another positive feedback loop with a warming climate. As the ocean acidifies, phytoplankton that produce calcium carbonate shells will be selected against and phytoplankton that do not build shells will have a competitive advantage. The fewer phytoplankton that build calcium carbonate that sink into the deep ocean, the less carbon dioxide the ocean will be able to adsorb, and the higher the concentration of carbon dioxide in the atmosphere available to continue to warm the planet.

E. Taking action—The need for sustained ocean observations

Earth's climate is now changing more rapidly than at any time in human history. The accumulation of greenhouse gases in the atmosphere will continue and the impacts describe above will worsen. As a result, this country will be increasingly called on to make complex decisions about how to manage and mitigate the impacts of climate change. We will be better able to make these decisions if we have the tools in hand to model and predict changes in the climate system. This will require a national commitment to increase investment to advance the field of climate modeling, continued support for sustained, high quality, ocean observations to power the models, and targeted experimental and field work to address outstanding questions raised by model uncertainty surrounding the biological and chemical processes that are key drivers of the ocean carbon cycle.

1. Modeling

To study how the atmosphere and the different layers of the ocean interact to predict changes in climate, scientists build computer models. At a basic level, within the model the surface of the Earth is divided into squares and each square includes a series of mathematical equations that represent the processes being modeled. These equations are based on physical and chemical laws. The more refined the model, the smaller squares and the more information they contain.

Modelers have a saying—"garbage in, garbage out." For a model to accurately represent that is happening in the real world, it must have data and lots of it. To predict changes in climate, models need data on the temperature, salinity, and carbon concentrations in the surface and deep ocean, global sea ice distribution, surface stress and surface and deep ocean currents, and heat flux. They also need data on the movement of freshwater from the land via rivers, glaciers, and ice sheets. These data need to be collected over decadal time scales and be global in scope. To predict climate, we also need to understand ocean biology because biology controls carbon uptake and regeneration at the base of the ocean food web.

2. Types of observations needed—heat, freshwater, and carbon

A common tool used by scientists is the construction of budgets for important variables in the model. As an oceanographer who studies nitrogen, I would construct nitrogen budgets to show where nitrogen was coming from, such as a river or a waste water treatment plant, and where it was going, such as into phytoplankton or bacteria. A recent National Academies (2017) report identified three global budgets that were needed to understand climate—heat, freshwater, and carbon. They were selected because they each are necessary to understand the climate system and to predict how it will change in the future. To truly quantify these three budgets requires a global ocean observing system where continuous, calibrated measurements are made over decades.

Heat—A heat budget is the balance between the heat absorbed by Earth from incoming solar radiation and outgoing heat escaping from Earth in the form of radiation. Slight changes in the balance would lead to Earth getting progressively warmer or cooler with each passing year.

Over the past 100 years, there has been a net gain in heat on Earth's surface. Ninety percent of this gain has been through ocean warming. The adsorption of heat by the ocean is one the reason why atmospheric temperatures at the Earth's surface

have not increased more (Fyfe *et al.,* 2016). This heat is transported throughout the surface and deep ocean currents. Currents in the deep ocean are controlled by small variations in temperature and salinity and are known as thermohaline currents. The greatest challenge for measuring global ocean heat content has been to sample a large enough number of sites around the globe and at enough depths throughout the ocean.

Freshwater—Less than 4 percent of the water on Earth is freshwater. Sixty-eight percent of this freshwater is locked up in ice and glaciers and another 30 percent is groundwater. Understanding the freshwater budget is important to understanding the salinity of the ocean. Salinity and temperature determine the density of water and so is an important control on ocean stratification and ocean circulation. Generally, temperature is more important and the basic structure of the ocean water column as warm water at the surface and progressively colder water as one moves deeper. Freshwater, and its effect on salinity, however, can change this relationship drastically. Areas where there is a lot of freshwater input, such as at a river outflow, regions with high rates of precipitation, or where sea ice is melting are areas where salinity is reduced making the water less dense. This less dense water remains at the surface, creating a barrier to mixing with the water below. This stratification reduces mixing of heat and gases between the surface and deep ocean thus impacting the heat balance in the region.

Carbon—The global carbon cycle is made up of pools of carbon and the processes that move this carbon from the atmosphere, surface and deep ocean and the sediment below. The cycle includes inorganic carbon, which is non-living carbon such as carbon dioxide and organic carbon, which is carbon that have been incorporated into organisms or the dissolved organic carbon they produce. This cycle is important to climate for a number of reasons, but primarily because of its control on concentrations of the greenhouse gas, carbon dioxide, and the huge effect carbon dioxide has on the heat balance of the planet.

An understanding of the carbon budget is essential to predicting future atmospheric carbon dioxide concentrations under different scenarios. Closing the carbon budget will require sustained observations of how much carbon dioxide the ocean absorbs and what happens to that carbon once it enters the ocean. This information is needed to predict how much carbon dioxide will be absorbed by the ocean in the future and the impact it will have on ocean acidification.

3. How do we collect the data we need?

We are not currently able to close the budgets described above, meaning that there are unaccounted for sources or sinks of heat, freshwater, and carbon in the ocean. To address this deficit, we need to develop methods or improve existing methods for some parameters and expand observations into areas of the ocean that are poorly sampled.

A successful global ocean observing system will use a suite of measurement and instrument approaches to provide complete coverage at the time scale of relevance to the measurement being taken. There are a number of ways to collect ocean data including the use of unmanned autonomous platforms such as satellites, buoys, floats, gliders and moorings. All of these approaches require that methods and instrumentation are available and able to withstand the incredibly harsh, corrosive ocean environment.

Suitable approaches exist for many physical and a few chemical variables such as temperature, salinity, the strength and direction of currents, carbon dioxide concentrations and pH. In the case of most chemical and biological measurements (such as trace metals, bacterial abundance, phytoplankton pigments, grazing rates to name just a few) autonomous methods and instrumentation do not exist or are cost prohibitive. These data can only be collected by scientists on board ships and so will remain severely limited in number and geographic scope. This lack of data is a strong impediment to understanding Earth's climate system.

4. International cooperation

The United States has been a leader in the development and deployment of ocean observing systems. We cannot do it alone, however, nor should we want to. Support for United States scientists to participate and lead international programs in climate modeling and ocean observations should be a priority. Coordinated international programs provide the opportunities to share the financial cost of long-term observing systems, improve the quality of the measurements taken through a robust program of intercalibration, and serve as an important route for science diplomacy. When nations collaborate to address common problems, partnerships are forged that can extend well beyond the original issue that brought the nations together.

An excellent example is the ARGO float program, which collects high quality profiles of temperature and salinity in the upper 2000 m of the ocean. There are currently 3875 ARGO floats in the ocean, purchased and deployed by 34 countries with nearly another 20 countries contributing to the program through field assistance or data analysis. The floats move passively with the current, slowly moving up and down the water column. When they reach the surface, they transmit their position and the data they collected to a data repository. ARGO has transformed our understanding of ocean currents. Additional sensors for oxygen and nitrogen (nitrate) have been developed and deployed on a small subset of the floats. Investment to increase the number of chemical and biological parameters that can be measured with the floats would be money well spent.

5. Workforce development

To address the issues outlined above, the United States will also require a highly skilled workforce. Increasing investment now into STEM education across the United States is necessary to support a sustained system of climate observations into the future. We also do not need to go it alone. For decades, the best and the brightest around the world wanted to come and be trained at institutes of higher learning in the United States and we welcomed them. We are fortunate that many of them chose to stay, and our Nation benefitted immensely from the skill, passion and innovation they brought. Those that chose to return home or go elsewhere, took with them a better understanding of our republic and lasting relationships with our citizens.

We now live in an era marred by terrorism and in our fear, we are making it increasingly more difficult for students to come to the United States and then to stay once they are trained. If I had to name one thing that most frightens me about the future of this country—this is it. The technological challenges in the future will be immense and we will only solve them by bringing together a wide array of viewpoints, perspectives, and experiences from across this great nation and around the world. I want the best and the brightest to be on our team. We should welcome them, train then well, and then staple a green card to every PhD diploma to encourage them to stay.

F. Conclusion

With the large increase in greenhouse gases that mankind has released into the atmosphere, we are conducting a massive experiment on the only planet we have. To know how best to protect ourselves from and respond to the changes in our climate, the United States should commit to sustained investment in four things—climate modeling, collecting the global ocean observations of key physical variables, developing the tools needed to generate global observations of key chemical and biological parameters, and training the workforce needed to do all three successfully. I emphasize the word sustained, because programs that can lay out workplans over the course of a decade or more will be more productive and better able to leverage resources than shorter term initiatives. Finally, the priorities for initiatives in modeling and data collection should be generated by leaders in the respective scientific disciplines and be done in the context of international collaborations.

G. Citations

Arrigo KR. 2014. Sea ice ecosystems. Annual Review of Marine Science. 6:13.1–13.29. doi 10.1146/annurev-marine-010213-135103.

Azevedo, LB, AM DeSchryver, AJ Hendriks, MAJ Huijbregts. 2015. Calcifying species sensitivity distributions for ocean acidification. Environmental Science and Technology. 49(3): 1495–1500. doi:10.1021/es505485m.

Bograd, SJ, CG Castro, E DiLorenzo, DM Palacios, H Bailey, W Gilly, and FP Chavez. 2008. Oxygen declines and the shoaling of the hypoxic boundary in the California Current. Geophysical Research Letters. 35(12): L12607. doi:10.1029/2008gl034185.

Comiso, JC and DK Hall. 2014. Climate Trends. In: *The Arctic as Observed from Space.* Wiley Interdisciplinary Reviews: Climate Change. 5: 389–409. Doi:10.1002/wcc.277.

Deutsch, C, H Brix, T Ito, H Frenzel, and L Thompson. 2011. Climate-forced variability of ocean hypoxia. Science. 33: 336–339.

Diaz, RJ and R Rosenberg. 2008. Spreading dead zones and consequences for marine ecosystems. Science. 321(5891): 926–929.

Environmental Protection Agency. 2013. Impacts of climate change on the occurrence of harmful algal blooms. EPA 820–S–13–001.

Fyfe, J. C., G. A. Meehl, M. H. England, M. E. Mann, B. D. Santer, G. M. Flato, E. Hawkins, N. P. Gillett, S.-P. Xie, and Y. Kosaka. 2016. Making sense of the early-2000s warming slowdown. Nature Climate Change 6(3):224–228.

Hayhoe, K, DJ Wuebbles, DR Easterling, DW Fahey, S Doherty, *et al.,* 2018: Our Changing Climate. In: *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II.* Reidmiller, DR, CW Avery, D. Easterling, KE Kunkel, KLM Lewis, TK Maycock, and BC Stewart, Eds. U.S. Global Change Research Program, Washington, DC, USA, pp. 72–144. doi: *10.7930/NCA4.2018.CH2.*

Jewett, L and A Romanou. 2017: Ocean acidification and other ocean changes. In: *Climate Science Special Report: Fourth National Climate Assessment, Volume I,* Wuebbles, DJ, DW Fahey, KA Hibbard, DJ Dokken, BC Stewart, and TK Maycock, Eds. U.S. Global Change Research Program, Washington, DC, USA, 364–392. *http://dx.doi.org/10.7930/J0QV3JQB.*

Jones, GP, MI McCormick, M Srinivasan and JV Eagle. 2004. Coral decline threatens fish biodiversity in marine reserves. Proceedings of the National Academy of Sciences of the United States of America. 101(21): 8251–8253.

Khatiwala, S, F Primeau, and T Hall. 2016. Reconstruction of the history of anthropogenic CO_2 concentrations in the ocean. Nature. 462: 346–349.

Laidre, K, H. Stern, M. Kovacs, L Lowry, SE Moore, *et al.,* 2015: Arctic marine mammal population status, sea ice habitat loss, and conservation recommendations for the 21st century. Conservation Biology. 29 (3): 724–737. *http://dx.doi.org/10.1111/cobi.12474.*

Le Quéré, C, RM Andrew, P Friedlingstein, S Sitch, J Hauck, *et al.,* 2018. Earth System Science Data. 10: 1–54. doi: 10.5194/essd-10–2141–2018.

Lucey, SM and JA Nye. 2010. Shifting species assemblages in the Northeast U.S. continental shelf large marine ecosystem. Marine Ecology Progress Series. 415: 23–33.

Miller, J, E Muller, C Rogers, R Waara, A Atkinson, KRT Whelan, M Patterson, and B Witcher. 2009. Coral disease following massive bleaching in 2005 causes 60 percent decline in coral cover on reefs in the U.S. Virgin Islands. Coral Reefs. 28 (4): 925–937. doi.org/10.1007/s00338–009–0531–7

National Academies of Sciences, Engineering, and Medicine. 2017. *Sustaining Ocean Observations to Understand Future Changes in Earth's Climate.* Washington, DC: The National Academies Press. *https://doi.org/10.17226/24919.*

NOAA State of the Climate: Global Climate Report for Annual 2017. National Centers for Environmental Information, published online January 2018, retrieved on February 4, 2019 from *https://www.ncdc.noaa.gov/sotc/global/201713.*

NOAA Fisheries, 2017: Fisheries Economics of the United States, 2015. NOAA Technical Memorandum NMFS–F/SPO–170. NOAA National Marine Fisheries Service, Office of Science and Technology, Silver Spring, MD, pp 245.

Paulmier, A and D Ruiz-Pino. 2009. Oxygen minimum zones (OMZs) in the modern ocean. Progress in Oceanography. 80(3): 13–128.

Pershing, AJ, RB Griffis, EB Jewett, CT Armstrong, JF Bruno, *et al.,* 2018: Oceans and Marine Resources. In *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II,* Reidmiller, DR, CW Avery, D. Easterling, KE Kunkel, KLM Lewis, TK Maycock, and BC Stewart, Eds. U.S. Global Change Research Program, Washington, DC, USA, pp. 353–390. doi: *10.7930/NCA4.2018.CH9.*

Pratchett, MS, PL Munday, SK Wilson, MAJ Graham, JE Cinner, DR Bellwood, GP Jones, NVC Polunin, and TR McClanahan. 2008. Effects of climate-induced coral bleaching in coral-reef fishes: Ecological and economic consequences. Oceanography and Marine Biology: An Annual Review. 46: 251–296.

Record, NR, JA Runge, DE Pendleton, WM Balch, KTA Davies, AJ Pershing, CL Johnson, K. Stamieszkin, R. Ji, Z Fend, SD Kraus, RD Kennedy, CA Hudak, CA Mayo, C Chen, J Salisbury, CRS Thompson. 2019. Rapid climate-driven circulations changes threaten conservation of endangered North Atlantic Right Whales. Oceanography. *https://doi.org/10.5670/oceanogr.2019.201.*

Riebelsell, U, N Alberle-Alzahn, EP Achterberg, M Algueró-Muñiz, S Alvarez-Fernandez, J Arístegui, LT Bach, M Boersma, T Boxhammer, W Guan, M Haunost, HG Horn, CR Loscher, A Ludwig, C Spisla, M Sswat, P Strange, and J Taucher. 2018. Toxic algal bloom induced by ocean acidification disrupts the pelagic food web. Nature Climate Change. 8: 1082–1086.

Rogers, CS and EM Muller. 2012. Bleaching, disease and recovery in the threatened scleractinian coral *Acropora palmata* in St. John, U.S. Virgin Islands: 2003–2010. Coral Reefs. 31(3): 807–819. https:/doi. org/10.1007/s00338–012–0898–8

Schmidtko, S, L Stramma, and M. Visbeck. 2017. Decline in global oxygen content during the past five decades. Nature. 542: 355–339.

Schoepf, V, M Stat, JL Falter, MT McCulloch. 2015. Limits to the thermal tolerance of corals adapted to a highly fluctuating, naturally extreme temperature environment. Scientific Reports. 5: 17639. doi: 10.1038/srep17639

Sweet, W, J Park, J Marra, C Zervas, and S Gill. 2014. Sea level rise and nuisance flood frequency changes around the United States. NOAA Technical Report NOS CO–OPS 073. 58 pg.

Stramma, L, ED Prince, S Schmidtko, J Luo, JP Hoolihan, M Visbeck, DWR Wallace, P Brandt, and A Körtzinger. 2012. Expansion of oxygen minimum zones may reduce available habitat for tropical pelagic fishes. Nature Climate Change. 2: 33–37.

Taylor, PC, W Maslowski, J Perlwitz, and DJ Wuebbles. 2017. Arctic changes and their effects on Alaska and the rest of the United States. In: *Climate Science Special Report: Fourth National Climate Assessment, Volume I.* Wuebbles, DJ, DW Fahey, KA Hibbard, DJ Dokken, BC Stewart, and K Maycock, Eds. U.S. Global Change Research Program, Washington, DC, USA, 303–332. http://dx.doi. org/10.7930/J00863GK

USGCRP. 2018. Second State of the Carbon Cycle Report (SOCCR2): A Sustained Assessment Report. Cavallaro, N, G Shrestha, R Birdsey, MA Mayes, RG Najjar, SC Reed, P Romero-Lankao, and Z Zhu (eds). U.S. Global Change Research Program, Washington, D.C., USA, 878 pp. https://doi.org/10.7930/SOCCR2.2018.

Vaughan, DG, JC Comiso, I Allison, J Carrasco, G Kaser, *et al.,* 2013. Observations: Cryosphere. TF Stocker, D Qin, G–K Plattner, M Tignor, SK Allen, J Boschung, M Nauels, Y Xia, C Bes, PM Midley, Eds. Cambridge University Press. Pg 317–382.

Senator GARDNER. Thank you, Dr. Bronk.

Dr. Horton.

STATEMENT OF RADLEY HORTON, LAMONT ASSOCIATE RESEARCH PROFESSOR, COLUMBIA UNIVERSITY

Dr. HORTON. Thank you, Chairman Gardner, Ranking Member Baldwin, and the other distinguished members of the Committee. My name is Radley Horton and I am Associate Research Professor at Columbia University's Lamont-Doherty Earth Observatory.

Extreme weather events, such as tropical storms, heat waves, heavy rain events, and drought threaten the economic livelihood of our Nation and the health and safety of our communities. In 2017, Hurricane Harvey inflicted an estimated $125 billion in damages, with 200,000 homes affected. In 2012, a drought caused $33 billion in losses, affecting multiple states. In light of the growing Federal, State, and local costs of extreme weather events, continuing forecasting advances and enhanced communication of scientific information with decisionmakers are necessary preconditions for the increased preparedness, improved disaster response, and long-term resilience we are discussing.

And continued forecasting improvements of extreme events will require new data from the atmosphere, the ocean, the land, and the cryosphere, as well as improved models that can better reproduce the key physical processes and the ways that they interact and also interact with the complex human system components.

So to give one example of those complex system interactions in the western U.S., including Colorado, the observed increase in extreme wildfires since the early 1980s. These large fires are, indeed, putting human safety and assets at risk with potential cascading impacts across insurance markets and public utilities. Weather and climate are clearly a big part of the story, as today when an individual weather system passes through; it is facing a new baseline of higher temperatures and reduced snow pack that have essentially stacked the deck toward an easier ignition of those fire systems.

But forecasting fire risk also requires integration of other environmental data, such as historical forest management decisions and changes in the risk of new ignitions as people are moving to previously wild areas.

As another quick example of system interactions, the surface of the ocean has warmed more than 1 degree Fahrenheit since 1900, which again loads the dice, this time toward heavier rain events that penetrate far inland, also toward combinations of high heat and high humidity that put our vulnerable populations at risk and threaten overall outdoor labor productivity as well.

But as the weather bill of 2017 notes, advances in our scientific understanding of extreme events alone do not ensure societal risk reduction. Working with communities and businesses to help ensure that the most useful information is being generated and that it is being communicated as effectively as possible for diverse audiences, thereby adding value to existing Federal investments in scientific research, is critical.

One quick example is NOAA's regional integrated sciences and assessments program, or RISA. A team in the south central United States worked with the strategic petroleum reserve to identify strategies to secure the nation's 32-day, roughly $33 billion value, supply of oil in the face of hurricane-related storm surge along the Gulf of Mexico.

In the remainder of my time, I want to further emphasize how small shifts in long-term average conditions, what we call climate, can have a large affect on the frequency and magnitude of extreme weather events. It follows that if we hope to reduce economic and safety risks to the nation, climate must play a central role in research on extreme weather and its impacts.

Since 1900, global temperatures have increased by about 2 degrees Fahrenheit. So far this century, just with that small change, the U.S. has seen twice as many record-breaking high temperatures as low temperatures.

It is a similar story with sea level rise. We have only had an average change of 7 or 8 inches globally in sea level. It may sound like nothing, but as shown in figure 1, for some locations the past two generations have witnessed a 5 to 10fold increase in the number of days with nuisance flooding, flooding that disrupts business, transportation, and critical public services.

Now let us look at the future of coastal flooding, the next slide. And instead of looking at nuisance flooding, let us look at the big coastal floods, the 1 in 100 year events, the heights that flood insurance and zoning decisions are based upon. Even under the most optimistic sea level rise scenario imaginable of 1 to 2 feet of sea level rise by late this century, we see here that across the entire U.S., events, high water levels that used to happen once every 100 years, are going to be happening within the lifetime of the typical 30-year mortgage. And in some places, those high water levels could happen once every couple of years.

Along the coast, our homes and critical infrastructure are all vulnerable, but it is all Americans who suffer the economic costs of sea level rises. It is, after all, U.S. taxpayers who bear much of the bill for coastal damages. If ports are damaged, and we can expect

broader supply chain implications and economic disruption well inland.

Fortunately, through investments in science and science communication geared toward decisionmakers, there is great potential for risk reduction and new opportunities across the U.S. economy. Moody's Investors Service, a major credit rating agency, has put cities on notice that if they do not plan both for historical extreme weather events but also for emerging weather and climate risks, their credit ratings, and thus ability to finance future expenditures, may be at risk. Growing numbers of investors and companies are now making similar demands, while recognizing the opportunities for first movers in this space.

Thank you for inviting me to testify, and I look forward to our discussion.

[The prepared statement of Dr. Horton follows:]

PREPARED STATEMENT OF RADLEY HORTON, LAMONT ASSOCIATE RESEARCH PROFESSOR, COLUMBIA UNIVERSITY

Mr. Chairman, and Members of the Subcommittee, my name is Radley Horton. I am an Associate Research Professor at Columbia University's Lamont-Doherty Earth Observatory. Thank you very much for the opportunity to participate in this hearing. I have served as an author on the 3rd and 4th U.S. National Climate Assessments, and as a Lead Principal Investigator within NOAA's Regional Integrated Sciences and Assessments (RISA) Program. I speak to you today though in my personal capacity as a private citizen.

Extreme weather events, such as tropical storms, heat waves, inland flooding, and droughts, threaten the economic livelihood of our Nation and the health and safety of our communities. In 2017, Hurricane Harvey caused an estimated $125 billion in losses, with an estimated 200,000 homes experiencing damage. Ongoing flooding in the Upper Midwest is sure to produce agricultural losses alone in the billions of dollars, and extreme drought across much of the U.S. in 2012 caused $33 billion in losses (NCEI, 2019). In light of growing federal, state, and local costs of extreme weather events, preparedness and early warning to reduce vulnerabilities is critical. Better forecasts, and enhanced communication of scientific information with decision-makers, are necessary preconditions for increased preparedness, improved disaster response, and long-term resilience.

As my colleagues have described, we are seeing rapid advances in scientific understanding and forecasting of extreme weather events, but continued success will hinge on continued investment in the science, and in insuring that information is communicated in ways that can benefit decision-making.

Extremes events operate across a range of time and space scales, from for example: a tornado less than one mile in diameter that may touch down for only minutes; to: a drought that may span half the U.S. and persist for several years. Our forecasting and prediction of these events must similarly range from the traditional multi-day weather forecast, through the subseasonal (two weeks to 3 months), and out to the seasonal and multi-decadal scales. Continued forecast improvements across these scales will require new data—from the atmosphere, ocean, land, and cryosphere—as well as improved models that can better reproduce the key physical processes and interactions among these complex systems, including our human systems.

As one example, the surface of the ocean has warmed more than one degree Fahrenheit since 1900, which loads the dice towards (1) heavier rain events extending far inland, and (2) combinations of high heat and humidity that put the health of our vulnerable populations, as well as outdoor labor productivity, at risk. But more research, with the best models and the latest data, is needed to understand just how much these extreme events will be affected by ocean temperature extremes. Similarly to ocean temperatures, changes in Arctic sea ice—volume had declined by more than 50 percent in the past 40 years—are impacting extreme weather events in the U.S., but our understanding of exactly how remains in its infancy. More data and modeling are urgently needed given the rapid changes we are observing in the Arctic, and the potential implications for National Security.

As another example, in the western United States, including Colorado, an observed increase in the number of large wildfires since the 1980s is putting human

health and assets at risk, with potential cascading impacts ranging from insurance markets to the financial health of utilities (Wuebbles *et al.,* 2017). Weather and climate are clearly a large part of the story, with the 'noise' of individual weather systems encountering a 'signal', or new baseline, of warmer average temperatures and long-term decline in mountain snow pack. But forecasting fire risk also requires integration of environmental data such as historical forest management decisions, risk of new ignitions, and how dry the fuel source is.

As a final example of the need to integrate diverse types of information to produce the best forecasts, marine heat waves, which now occur against a backdrop of warmer baseline ocean temperatures, are interacting with emerging ocean acidification and in some regions de-oxygenation, to threaten our fisheries and coastal ecosystems in complex ways.

But as NOAA's Weather Bill of 2017 acknowledges, advances in our scientific understanding of extreme events alone do not ensure societal risk reduction. Working with communities and businesses helps ensure that the most useful information is being generated, and that it is being communicated as effectively as possible for diverse audiences. I'd like to briefly describe one model for how scientists can work hand-in-hand with stakeholders and decision makers to make scientific research and information responsive to their needs, adding value to existing Federal investments in scientific research.

NOAA's RISA team in the south-central U.S. worked with the Strategic Petroleum Reserve to identify strategies to secure the Nation's 32-day, $33 billion, supply of oil in the face of hurricane-related storm surge along the Gulf of Mexico. After Hurricane Sandy inflicted $20 billion in damages in the greater New York Metropolitan Region, our RISA team partnered with local, state, and Federal entities, including the USACE and FEMA, to provide the science foundation and tools to support for example NYC's $20 billion resilience plan (Horton *et al.,* 2016).

In the remainder of my time, I want to emphasize a little appreciated point: that small shifts in long-term average conditions—what we call climate—can have a large effect on the frequency of extreme weather events. Higher average temperatures have already loaded the dice towards more heat extremes and fewer cold extremes, just as sea level rise is already causing coastal flooding to happen more often than it used to, with trillion-dollar implications that extend to every state. It follows that if we hope to reduce economic and safety risks to the nation, climate changes must play a central role in research on extreme weather and its impacts.

Since 1900, global temperatures have increased by about 2 degrees Fahrenheit (Wuebbles *et al.,* 2017). One could be forgiven for initially thinking, 'so what'? or 'how could 2 degrees matter?' given the much larger temperature variations we experience from one day to the next. But with 2 degrees of warming, record high temperatures become much more common, and record low temperatures much less common. In fact, so far this century the U.S. has experienced roughly twice as many daily record high temperatures as low temperatures.

It is a very similar story with sea level rise. Globally the oceans have 'only' risen about 7–8 inches since 1900 (Wuebbles *et al.,* 2017). How could that matter, when for many places the elevation change over the course of six hours between high tide and low tide is a few feet?

Sea level rise means more frequent coastal flooding and more intense/higher magnitude coastal flooding (Wuebbles *et al.,* 2017). Already we are seeing nuisance (also known as 'sunny-day') flooding happen far more often than it used to across the U.S. coastline, as shown in Figure 1. For some locations, the past two generations have seen a 5 to 10-fold increase in the number of days with nuisance flooding. (It should be noted that some of these places, including the Mid-Atlantic states, have had more sea level rise than the global average, but even for those states that have not, the trend towards more nuisance flooding is clear.) From Miami to Norfolk, this means for example: (1) more stores unable to open for normal business, with associated ripple effects on the economy; (2) people not able to drive home along their normal routes, leading to delays, and 3) more water in people's basements. These events perhaps deserve to be called a mere 'nuisance' when they only happen a few times per year—but at what point does it become something more than a nuisance?

Now lets look to the future of coastal flooding. And instead of looking at nuisance flooding, lets look at the big coastal floods—what are colloquially known as the '1 in 100 year' events—heights that flood insurance, and zoning decisions are made based upon (Figure 2). Lets take the most optimistic scenario sea level rise scenario imaginable for late this century. With just one to two feet of sea level rise, and even if coastal storms do not change at all, the 1 in 100 year high water levels of the past become events that for most of the U.S. coast will be experienced within the 30-year lifetime of the typical home mortgage. In some areas, these high water levels could happen every couple of years in the future. Rather than focusing on the

exact numbers in any one location, I would encourage you to note how the statistics shift strongly across the entire U.S. And once again, this is a low-end sea level rise scenario, and one that includes no assumptions about coastal storms changing in the future. For hurricanes, this assumption is probably somewhat optimistic, since the balance of evidence suggests that major hurricanes will become more frequent and intense, in large part due to the warming of the upper oceans (Weubbles *et al.,* 2017).

But sea level rise does more than just cause more frequent flooding. It means that when a coastal storm makes landfall, additional areas are flooded that would not have flooded before. And deeper floodwaters, which allow for greater wave penetration, cause more economic damage and loss of life. If the foot of sea level rise in the Greater New York/New Jersey Metropolitan Region since 1900 had somehow not occurred, 2012's Superstorm Sandy would have flooded the residences of 80,000 fewer people (Climate Central 2013; Miller *et al.,* 2013).

The more frequent and intense coastal flooding brought on by sea level rise will impact all Americans. Along our coasts are assets worth trillions of dollars. From our homes, to critical service providers, to critical infrastructure including interstates like I–95, rail lines including Amtrak, airports, and municipal water treatment plants.

And sea level rise is also a public health and safety issue. It means less time to evacuate from low lying areas in advance of a coastal storm, and greater risk of injury and death for those vulnerable members of our communities who are unable to evacuate.

And just as all Americans suffer when the health and safety of any American is imperiled, so too will all Americans suffer the economic costs of sea level rise. It is after all U.S. taxpayers who bear much of the bill for coastal flood damages. And coasts are economic hubs for the entire nation. Our ports, which almost by definition are vulnerable to sea level rise, serve inland interstates and rail systems, as well as regional distribution centers. If ports are damaged or operating at reduced capacity, we therefore see supply chain implications, and economic disruption.

And then there are the national security implications. From NASA's Kennedy Space Center on Florida's Space Coast and Johnson Space Center outside Houston, to Norfolk's Naval Base and shipyards, what happens along U.S. coasts can have global implications. Recent coastal storm damages made worse by climate change have led to billions in damages at an Air Force base and a Marine Corps camp.

And of course, extreme events interact. For example, for a low lying coastal city, even a small increase in rainfall intensity, combined with a small increase in a hurricane's storm surge could lead to a large increase in flooding if accompanied by even modest sea level rise.

To conclude, extreme events sit at the interface between great potential for advances in scientific understanding on the one hand, and great societal need on the other. Through investment in science and science communication geared towards the specific questions decision-makers are asking, there is thus great potential for risk reduction and new opportunities across the U.S. economy. It is becoming clear that groups such as large investors and infrastructure stewards realize that they must plan for rapidly evolving risks of extreme weather events. As one of many examples, Moody's Investors Service, a major credit ratings agency, has put cities on notice that if they do not plan for both historical and emerging weather and climate risks, their credit ratings, and thus ability to finance future expenditures, may be at risk. Growing numbers of investors and companies are now making similar demands, while recognizing the opportunities for first movers.

Thank you for inviting me to testify, and I look forward to our discussion.

References

Climate Central, 2003. Surging Seas Sea level rise analysis by Climate Central. Retrieved February 25, 2019, from *http://sealevel.climatecentral.org./*

Horton, R., Rosenzweig, C., Solecki, W., Bader, D., & Sohl, L. (2016). Climate science for decision-making in the New York metropolitan region. *Climate in Context: Science and Society Partnering for Adaptation,* 51–72.

Miller, K. G., Kopp, R. E., Horton, B. P., Browning, J. V., & Kemp, A. C., 2013. A geological perspective on sea-level rise and its impacts along the U.S. mid-Atlantic coast. *Earths Future,* 1(1), 3–18. doi:10.1002/2013ef000135

Moser, S. C., M. A. Davidson, P. Kirshen, P. Mulvaney, J. F. Murley, J. E. Neumann, L. Petes, and D. Reed, 2014: Ch. 25: *Coastal Zone Development and Ecosystems. Climate Change Impacts in the United States: The Third National Climate As-sessment,* J. M. Melillo, Terese (T.C.) Richmond, and G. W. Yohe, Eds., U.S. Global Change Research Program, 579–618. doi:10.7930/J0MS3QNW.

NOAA National Centers for Environmental Information (NCEI) U.S. Billion-Dollar Weather and Climate Disasters (2019). *https://www.ncdc.noaa.gov/billions/*

Sweet, W.V., R. Horton, R.E. Kopp, A.N. LeGrande, and A. Romanou, 2017: Sea level rise. In: *Climate Science Special Report: Fourth National Climate Assessment, Volume* I [Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, pp. 333–363, doi: 10.7930/J0VM49F2.

Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, B. DeAngelo, S. Doherty, K. Hayhoe, R. Horton, J.P. Kossin, P.C. Taylor, A.M. Waple, and C.P. Weaver, 2017: *Executive Summary of the Climate Science Special Report: Fourth National Climate Assessment, Volume I* [Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, 26 pp.

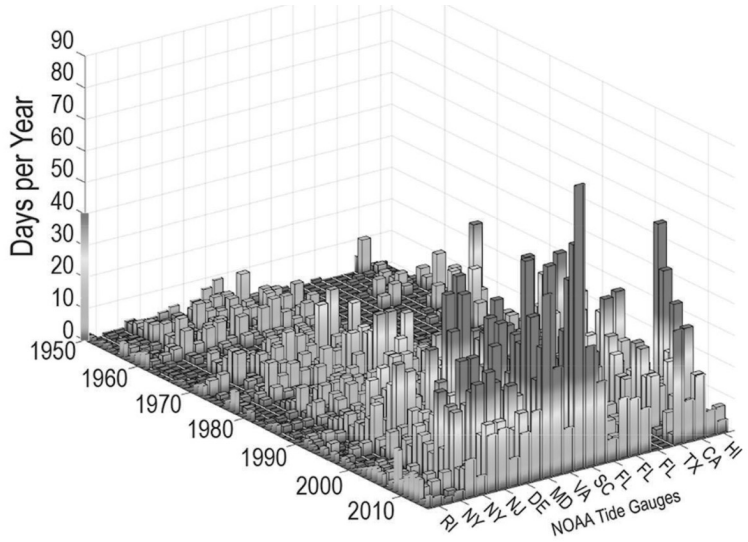

Figure 1. Tidal floods (days per year) exceeding NOAA thresholds for minor impacts at 28 NOAA tide gauges through 2015. Source: Sweet et al., 2017.

Figure 2. The amount of sea level rise (SLR) by 2050 will vary along different stretches of the U.S. coastline and under different SLR scenarios, mostly due to land subsidence or uplift. This figure shows how a 1.05-foot SLR by 2050 could cause the level of flooding that occurs during today's 100-year storm to occur more frequently by mid-century, in some regions as often as once a decade or even annually. All estimates include the effect of land subsidence. Source: Moser et al., 2014.

Senator GARDNER. Thank you, Dr. Horton.
Dr. Washburn.

STATEMENT OF ERIKA WASHBURN, PH.D., DIRECTOR, LAKE SUPERIOR NATIONAL ESTUARINE RESEARCH RESERVE

Dr. WASHBURN. Thank you, Chairman Gardner, Ranking Member Baldwin, and members of the Subcommittee.

I direct the Lake Superior Reserve administered by the University of Wisconsin-Madison's Division of Extension. I am also here representing the National Estuarine Research Reserve Association nonprofit, which represents all 29 designated reserves around the Nation.

For 46 years, the reserves have served, as a national network of coastal and estuarine places in a Federal-State partnership that works directly in response to community needs to deliver science, education, and stewardship to track the health of our coastal systems and understand how they are changing.

We leverage the expertise and resources of our Federal partner, NOAA, and collaborate with many more partners all over the Nation. We work in a non-regulatory, non-advocacy framework on issues that communities care about through such things as a system-wide monitoring program which collects data every 15 minutes, adding up to over 40 million publicly available data points every year for communities to use for planning purposes.

I work on the shores of Lake Superior, the world's largest body of freshwater. Every day I drive between Wisconsin and Minnesota over the St. Louis River, home to the largest freshwater port in the world. The resilience of our community is connected to our coast. Yet, those are changing rapidly. Today I will focus on three aspects of change: water levels, habitats, and changing water temperatures and chemistry.

Right now, Lake Superior is 15 inches higher than the average over the last century. Region-wide, we are projected to reach or exceed record high water levels, coupled with more frequent and intense storms. This increases our risk for severe coastal flooding. Last month, the City of Ashland suffered heavy rains forcing 5 million gallons of untreated sewage into Lake Superior. In 2012, as my first image shows, a 500-year storm destroyed much infrastructure in the twin ports and surpassed over $100 million in damage. In the past 7 years, our region has had nine Federal disaster declarations related to storms and flooding. There is another image here that shows a close-up.

The ability to predict and plan for changing water levels is critical and complicated. Yet, our many partners and we are helping coastal communities adapt. Duluth residents are piloting natural infrastructure as a strategy to reduce storm damage. Lake Michigan communities have access to tools to manage bluff erosion so they can protect their property from landslides.

Like water levels, our coastal habitats are changing, threatening native species while allowing invasive species to take hold. Changing water levels and habitat threaten the future of wild rice, or manoomin, which is very important for our partners of the Fond Du Lac Band of Lake Superior Chippewa. This threatens Ojibwe heritage and identity. Children cannot be named without wild rice as part of the ceremony.

Reserves work on habitat conservation and restoration for wild rice and other things by advancing such topics as natural shorelines to mitigate flooding and increase resilience. With the Lake Superior and Ohio reserves, we have permanent monitoring stations that provide data decisionmakers need to protect water quality and habitat. Our reserve is also partnering on enhancing restoration and tourism opportunities, as well as improving visitor experiences, on Wisconsin Point, a beloved local beach.

But warming waters changes everything. When I came to Lake Superior 7 years ago, everyone referred to algal blooms as something for the lower lakes, like Lake Erie. They could not happen in Superior. It was too cold, too big, too oligotrophic or nutrient poor. But we have had three documented algal blooms in the last 2 years. Research tells us that storms and sediment plumes play a role. Research also shows that Lake Superior is warming faster than almost any lake on Earth, and this is clearly climate-driven.

The complicated research, however, focuses on the human dimensions, how to communicate risk from warming waters, how to connect decisions made up watershed with degraded water quality on the coast. At Lake Superior Reserve, we are working with the public health community to reduce blooms by improving monitoring, and Milwaukee decisionmakers will have access for real-time early warning detections of blooms.

These accelerating patterns of change are affecting everything about how we live, work, and play on all of our coasts. In the Great Lakes, we expect public health will suffer, but at-risk communities are more vulnerable to climate change and tribal nations especially so.

At the Lake Superior Reserve, we are at the forefront of work examining the mental health impacts of solastalgia, or the grief and anxiety that comes from the loss of landscapes, place, and identity due to environmental change. We are joined by our colleagues and travel communities to bring the strength of traditional ecological knowledge and an understanding of the impacts of lost heritage identity and place. Sadly, their work is helping us see parallels with what Lake Superior residents are all beginning to experience in front of our eyes.

The 29 reserves and all of our many partners will continue to support the monitoring and interdisciplinary research that coastal communities need. Thank you again to Congress for your investments in all of our programs. We could not have accomplished what we have so far without it. Yet it is critical that these investments continue to ensure that future science is focused on issues of importance to our coastal communities, neighbors, families, and friends.

Thank you.

[The prepared statement of Dr. Washburn follows:]

PREPARED STATEMENT OF ERIKA WASHBURN, PH.D., DIRECTOR, LAKE SUPERIOR NATIONAL ESTUARINE RESEARCH RESERVE

Chairman Gardner, Ranking Member Baldwin, and Members of the Subcommittee, my name is Erika Washburn. I am the director of the Lake Superior National Estuarine Research Reserve, which is administered by the University of Wisconsin-Madison's Division of Extension. I submit this testimony in my capacity as director of one of two reserves in the Great Lakes and as a member of the National Estuarine Research Reserve Association, which represents 29 designated reserves around the Nation.

I appreciate this opportunity to speak about the science associated with climate change from the perspective of a national network of coastal and estuarine places and a federal/state partnership that works directly with coastal communities. For 46 years, the Reserves have delivered science, education, and stewardship to track the health of estuarine and coastal systems and understand how they are changing. I would like to thank Congress for its vision and funding for this important work.

Together, reserves encompass more than 1.4 million acres of locally-owned, special places in 22 states and territories. Since 2011, we've engaged more than 4,000,000 scientists, educators, students, and visitors in research, monitoring, and education. We work in a non-regulatory, non-advocacy framework on issues that coastal communities care about: clean water, safety, informed citizens, abundant fisheries and healthy habitats. Climate change affects all of these.

Of relevance is our unique System-wide Monitoring Program, designed to track environmental change and inform coastal resource management and science. Together, we manage 280 monitoring stations that—every 15 minutes—take readings on water quality, pollution, habitat change, sea level rise and weather. We produce more than 40 million, publically available data points every year. Communities rely

on this to plan for extreme weather, manage fisheries, assess storm damage, and more.

Reserves leverage the expertise and resources of our partner, the National Oceanic and Atmospheric Administration (NOAA), which provides the most current and advanced coastal and climate science and data. We collaborate with Federal and state agencies, Tribal entities, local governments, school districts, businesses and academic institutions. We address the multi-faceted needs of coastal communities, informing critical decisions that impact the economy, public health, and safety.

I work on the shores of Lake Superior—the world's largest body of freshwater by surface area. Every day, I drive back and forth between Wisconsin and Minnesota over the St. Louis River, home to the largest freshwater port in the world. More than 35 million short tons of cargo pass through here annually, to cities throughout the Great Lakes and beyond. 23 million Americans live within the Great Lakes basin and we contribute more than $3 trillion in GDP with our maritime economy. Our economic health and the resilience of our communities is firmly connected to our coasts. As a social scientist, and anthropologist, I have worked to understand the connections between people and these places.

Today I will focus on three aspects of climate science that are of particular importance to people in coastal communities: changing water levels; changing habitats, and changing water temperatures and chemistry.

Changing Water Levels

My office sits 10 feet from the St Louis River Estuary and a short boat ride to the open waters of Lake Superior. Right now, water levels are 15 inches higher on average than they were between 1918 and 2017. April precipitation topped historic averages by at least 24 percent. Region-wide, we are projected to reach or exceed record high water levels. NOAA and others warn that, coupled with more frequent and intense storms, this increases our risk for severe coastal flooding like what is happening today in northwest Ohio and southeast Michigan.

Understanding the relationship between lake levels and climate change is complicated, involving regional models, ground and surface water, and ice cover change. Lake levels and flooding have increased because we are experiencing more frequent and intense precipitation events and more rain than snow in winter. Last month the City of Ashland suffered heavy rains which forced five million gallons of untreated sewage into Lake Superior. Last year, Wisconsin's coastal counties experienced multiple severe storms, *one* of which resulted in more than $3.5 million in damages. In 2012, a 500-year storm destroyed infrastructure, roads and businesses in the Twin Ports. Flood damage at our local university approached $24 million, while the Duluth area suffered $100 million in damage. In the past seven years, our region has had 9 Federal disaster declarations related to severe storms and flooding.

The ability to predict and plan for changing water levels is critical for all Great Lakes communities. It affects infrastructure, property values, shipping, dredging, public health, and quality of life. Analysis and modeling from NOAA's Great Lakes Environmental Research Lab is already focused on understanding the connection between global warming and lake levels to project future trends. However, scientists agree that further research is required to prepare communities as they plan for the future.

While we are grateful for past congressional support, continued Federal investment in reserves and other monitoring programs is needed. It makes good sense to forecast future changes accurately so that local governments have the information they need to invest in grey and natural infrastructure, reduce flooding, and minimize damage to roads, stormwater systems and businesses. The Lake Superior Reserve and our partners are already hard at work on these critical issues. I am happy to share some examples:

- Duluth residents are piloting natural infrastructure as a strategy to reduce storm damage, thanks to a collaboration between Minnesota Sea Grant and NOAA that developed tools to visualize potential flood impacts and gauge the use of natural infrastructure to mitigate flooding.
- Lake Michigan communities have access to better tools to manage bluff erosion, including a new device that measures bluff movement so residents can protect their property from landslides. Partners include the University of Wisconsin-Madison, Wisconsin Sea Grant, and the University of Michigan.

Many challenges brought about by changing water levels in the Great Lakes are shared by marine communities, and reserves are working with them to meet these head on.

- Florida's Flagler County now has access to improved modeling tools to support adaptation planning and flood management, thanks to our Guana Tolomato Matanzas reserve.
- Communities across the Gulf of Mexico have access to enhanced sea level rise data and storm surge models that they are using to assess the vulnerability of built and natural infrastructure. These tools were supported by our Florida, Mississippi, and Alabama reserves.
- In Texas, the City of Rockport is using a vulnerability assessment conducted by the Mission-Aransas reserve to reduce economic and property losses related to changing water levels.

Changing Habitats

Coastal habitats are rich, vibrant systems that serve as shelter and nursery for valuable fisheries and thousands of species of birds and wildlife. *But they are changing.* As water levels increase, temperatures warm, water chemistry changes, and storms intensify, habitats are lost or dramatically altered, native species struggle to survive and invasive species take hold. This impacts the survival of the very species that drew people to settle in coastal areas in the first place. In the Ojibwe origin story, their ancestors traveled around Lake Superior until they found a place where wild rice, or manoomin, grew on the water. Today, changing water levels and other factors threaten the future of wild rice—not just in our region where we partner with the Fond Du Lac Band of Lake Superior Chippewa—but across the upper Great Lakes. This threatens Ojibwe heritage and identity; children cannot be properly named without a wild rice ceremony.

Essential to coastal habitat conservation and restoration are advances in our understanding of natural shorelines as a way to mitigate flooding and increase ecological resilience. Reserves work with many partners to understand the biophysical science behind replacing hardened shorelines with natural features and the social and economic impacts of these investments. This requires a social science lens and the ability to pull together builders, contractors, engineers, scientists, managers and local decision makers to translate the science and explore potential solutions. Reserves do this well. Here are two examples.

- Permanent monitoring stations at the Lake Superior and Ohio reserves are providing data decision makers need to protect water quality, species, and habitat, while reducing community flooding. These stations track changes resulting from more intense storms, increased sediment, and nutrient runoff.
- Enhanced recreation and tourism opportunities are improving visitor experiences on Wisconsin Point, a beloved local beach, thanks to an ongoing restoration project supported by NOAA, the City of Superior, and the Lake Superior Reserve.

As a networked system of 29 reserves, we know salt marshes are struggling to keep pace with sea level rise, and communities are contemplating whether to support marsh migration in already crowded coastal watersheds. What will they lose? What will they gain? What are the costs? They must balance questions like these with ones about how best to protect or migrate infrastructure, property, and roads. All 29 reserves are helping communities address these questions with the best science, data, and information.

- Alaska's Kachemak Bay reserve supported a model of regional groundwater flows that is informing decisions to protect habitats for salmon, the state's most important fishery. This is of value to Alaskans because Coho and Chinook salmon depend on freshwater habitats that are changing due to reduced snowpack, altered rain patterns, and wetland drying.
- Florida's Apalachicola reserve provides science to address critical local issues, including the impact of salinity on the bay's oysters, which have suffered a 90 percent decline in recent years. Reserve monitoring tracks the influence of upstream water diversions, land use change, climate change, hurricanes, and other natural events on local water quality.
- Endangered native birds and fish have returned to the He'eia Estuary as a result of restoration, supported by monitoring and outreach from Hawaii's He'eia reserve. Their work removes invasive mangroves, encourages natural freshwater flows, restores habitat, provides food for communities, and supports management as a traditional Hawaiian ahupua'a.
- The invasive marsh grass Spartina—which was threatening the local oyster industry—was eradicated from Washington's Padilla Bay, as a result of a combined monitoring and restoration initiative. Today, regional resource managers

look to the reserve for information and guidance for invasive species removal and control.

Changing water chemistry and temperature

When I came to Lake Superior almost seven years ago, everyone referred to algal blooms as something for the lower Great Lakes, especially Lake Erie. They couldn't happen in Superior; it's the biggest, deepest, coldest, most oligotrophic (nutrient poor) Great Lake! Fast forward to today: there have been three documented algal blooms in the last two years. Why? Research tells us that storms and sediment plumes play a role. These events are expected to intensify. Even more concerning is scientific monitoring and modeling from the University of Minnesota Duluth's Large Lakes Observatory, which shows that Lake Superior is warming faster *than almost any lake on Earth.* And, the research shows, this is clearly climate driven.

Warming waters complicate everything. They compromise water quality, which impacts tourism and fisheries, accelerate habitat change, increasing the likelihood that native species will be overcome by invasives and—when combined with damaging storms and floods—put public health at risk. Along our marine coasts, warmer temperatures are contributing to ocean acidification, which threatens hard shelled creatures, like lobsters and oysters, around which many local economies have been built.

Some impacts of changing water temperatures are well understood. The really complicated science, however, focuses on the human dimensions of these problems. How to communicate risk? How to connect decisions made up watershed with degraded water quality on the coast? Social scientists such as anthropologists, economists, and communication experts are exploring questions like these in the context of climate projections.

It is critical that Congress continue to invest in science to understand trends in acidification, marsh migration, sea level rise, saltwater intrusion, and harmful algal blooms. By doing this, our partners in coastal communities will be better prepared to make decisions that mitigate economic loss and reduce risk to public health. Programs across the region are responding to the need to predict and manage harmful algal blooms:

- The Lake Superior reserve is working with the public health community to reduce algal blooms by improving monitoring efforts. This summer we will collect water samples immediately following storm events to better understand bloom formation.
- Milwaukee decision makers will soon have access to enhanced technology for real-time, early-warning detection of blooms, with support from Sea Grant. With support from NOAA and partners, this technology will provide forecasts to inform local governments and public health experts about risks to residents and tourists.

Through our national network, we know that coastal water temperatures, chemistry, and quality are in flux around the country. Communities are dealing with harmful algal blooms and dead zones, pollution from legacy industries and current events, amid the more basic biogeochemistry of wetlands. Here again, reserves are supporting their communities.

- Continuous monitoring from Florida's Rookery Bay reserve demonstrated that estuaries protected by conservation land are more resilient to large storms. During Hurricane Irma, reserve instruments captured the storm surge, extraordinary rainfall, and the subsequent dissolved oxygen crash. Fisheries monitoring showed that fish left the estuary when the oxygen crashed and returned as the oxygen levels return to normal.
- In Alaska, the Kachemak Bay reserve's potentially lifesaving shellfish toxin alerts are provided to state officials, commercial oyster farms, and thousands of recreational and subsistence shellfish harvesters.

Emerging Trends

As a social scientist, I would like to conclude with some observations on what all of this change will mean for people. In recent years, we have seen the warmest temperatures recorded, powerful storms, increased flooding from sea level rise and storm surge, devastating wildfires, and the melting of glaciers and polar sea ice. These accelerating patterns of change are affecting how everyone lives, works, and plays on all U.S. coasts. They affect businesses and industries, public health, and everyone's psychological well-being.

In the Great Lakes, we expect public health will suffer due to more extreme heat, increased water temperatures, degraded water quality, reduced air quality in urban

areas, changes to agricultural systems, and the spread of vector borne diseases like Lyme. Not all populations or communities will suffer these impacts equally. At-risk communities are more vulnerable to climate change, and tribal nations are especially so because of their reliance on threatened natural resources for their cultural, subsistence, and economic needs.

Research to address these challenges is becoming a larger part of the coastal science portfolio because communities demand it. They are calling for us to assess the vulnerabilities of people, alongside environmental concerns so they can better manage risks and increase overall resilience particularly as they relate to vulnerable populations.

At the Lake Superior Reserve, we coordinate a diverse network of experts to explore the human side of climate change. We are at the forefront of work examining the mental health impacts of solastalgia, or the grief and anxiety that comes from the loss of ecosystems, species, landscapes, and identity due to environmental change. This work involves natural and social scientists, public health and medical experts, social workers, and those serving on the front lines of tragedy. We are joined by our colleagues in Tribal communities who bring the strength of Traditional Ecological Knowledge and an understanding of the impacts of lost heritage, identity, and place. Sadly, their difficult work is helping us see parallels with what Lake Superior residents are all beginning to experience as the region changes in front of our eyes.

The Lake Superior reserve, the 28 sister reserves that make up our national system, and all of our many partners will continue to support the baseline monitoring and interdisciplinary research that coastal communities need to understand how climate change is influencing their lives and the places in which they live. We could not have accomplished what we have so far without strong Federal and state investments in coastal science programs embedded in local communities, or without the Research Reserve's System-wide Monitoring Program that continually assesses changing water levels, water quality and habitats. Thank you, again, to Congress for your investments in all our programs. It is critical that these continue if we are to ensure that future science is focused on issues of vital importance to our coastal communities, neighbors, families and friends.

Thank you for your time and consideration.

Senator GARDNER. Thank you, Dr. Washburn.

We will begin with questions, and I will start here with just a few and then turn it over to Senator Baldwin.

I understand the importance of investing in improved climate models—clearly the importance of investing in improved climate models. Today's models can give us pinpoint weather forecasts in the near term and help identify longer-term trends, including those caused by carbon pollution.

I would like to see future investments that move us beyond studying the climate and toward solving climate-related problems. We need models that produce sufficiently high confidence forecasts farther out into the future and drive significant public and private investment. Those investments will generally fall into two buckets: mitigation and adaptation. We will need adaptation in the near term, obviously, while we ultimately solve the problem with mitigation efforts in the longer term.

To aid our mitigation efforts, we need these models to be able to evaluate various carbon reduction and carbon capture technologies. We need to run various scenarios that evaluate the timing and magnitude of mitigation required.

And so, Dr. Washburn, beginning with you, in your testimony you talked about how the magnitude and rate of climate change will be dependent on whatever mitigation measures are taken. Have you considered how these models might be able to evaluate the efficacy of mitigation measures?

Dr. WASHBURN. So that is something where I wish I had some of my partners at the table to assist since I am an anthropologist.

So I rely heavily on a lot of the atmospheric scientists, lake-level modelers, and others.

I can say that the researchers will take those models. We provide data that ground truth some of those models and improve them. But we also take those models, package them up into information, make sure they are translated so that local decisionmakers and governments can actually use them and understand what they mean. And we do that through our programs and education and in coastal training with local decisionmakers.

And I guess I would say that we can add both ground truthing local data to enhance those models and improve them. We can also fine-tune the resolution of the data that is presented in those models by adding in our own data from the system-wide monitoring program. So we can bring a lot of really local fine resolution and information that the local communities can use.

Senator GARDNER. Thank you.

And then I would open that question up to anybody else on the panel who wanted to take a crack at that, if anybody does. Dr. Horton?

Dr. HORTON. Sure. Thanks.

I mean, I think you just articulated sort of a classic, sort of risk management problem, how to make long-term decisions in the face of key uncertainties.

One thing that is completely clear, though, is that the further we push the climate system by increasing greenhouse gas concentrations, temperatures causing changes in the ice sheets, for example, the greater potential for surprises, feedbacks that could include changes in the greenhouse gas emissions and carbon cycle of the planet itself.

I think you also raised some interesting ideas about ways that we could test possible future scenarios. For example, enhancing models so that you could in a local coastal scale see what happens if you put in, before actually buying one, a sea barrier, for a major sea wall. Can we model what effects that might have on sedimentation rates, for example, and start to get at some of these tradeoffs of different adaptation strategies?

I think there is also interesting work in the space of co-benefits between greenhouse gas mitigation efforts and adaptation efforts. Where can we find examples of benefits for both and avoid situations where they appear to be going against each other, which obviously we do not want?

Senator GARDNER. And I think that kind of gets to my next question, which was the sort of reverse engineering. Can we reverse engineer the model, so to speak, to identify new mitigation technologies or strategies? And I think you just kind of talked about how we could approach it in that direction. Did I hear you correctly?

Dr. HORTON. One thing certainly to highlight is that climate models are not just a tool for future predictions. We can use those models under past configurations, different amounts of CO_2 concentrations, for example, in the past to test things like how sensitive sea levels might be. The ice sheets might be to a given amount of warming. That gives us some ability to constrain the

projections, but it is not complete because conditions are unique today.

Senator GARDNER. Dr. Abdalati, did you want to add to that?

Dr. ABDALATI. To your point, the physics are the physics. They behave by certain physical principles. We test the physics, the quality of our models against past conditions events against present and emerging conditions.

So, yes, we can use models to test the efficacy of various mitigation strategies. We have used models to test the effectiveness of things like carbon capture to reduce the impact of carbon dioxide or the amount of carbon dioxide in the atmosphere. So the same physics that apply to weather forecasting, but tweaked for longer time scales, do apply to model forecasting and can be used to assess the efficacy.

There is still, though, a ways to go in the quality of these models to really nail things down. And this is why it has become politicized is because there are costs to mitigation. And so the fundamental question is, is the mitigation worth the cost? There are costs to not mitigating. And again, the question is, is the not mitigating worth the cost, if I said that correctly?

So all of this hinges on a robust understanding of the physical principles and the evolution of our climate system, which is why research in these areas is so important. I cannot stress enough the importance of de-politicizing this aspect. We have a challenge before us that will have consequences and that our approach can realize tremendous benefits, and to successfully meet those challenges requires understanding and that is what we are all pursuing.

Senator GARDNER. Thank you.

I will turn to Senator Baldwin now and then we will come back.

Senator BALDWIN. So, Dr. Washburn, you talked about some of the extreme events that have been experienced in northern Wisconsin on the shores of Lake Superior. I remember traveling to Ashland and Iron Counties in the first few months of my time as a United States Senator. In response to an extreme weather event that I was told was either 1,000- or a 500-year event. I was meeting with community leaders, often town chairmen and other town employees, who were, first of all, dealing with the immediate aftermath of rescuing people who might be cutoff from the community. But then also, beginning to assess damage and prepare for emergency declarations and a process whereby they may become eligible for Federal assistance.

I remember just 2 years later going to the same community and seeing some of the same infrastructure severely damaged; being told that it was either a 500-year or 1,000-year event. And as you note in your testimony, in the last 7 years, we have seen three events that might be called 500-year events.

So just for context, these events are basically defined as 500-year events because the old rainfall models suggest that they would happen only once in 500 years. But we have seen three in 7 years. The weather patterns clearly seem to be changing rapidly, and I am very concerned about our lack of preparation.

So as we work to address this issue, I think the first thing we need to know is what is coming. Right? Dr. Washburn, does the sci-

entific data tell us about how extreme weather events and other weather patterns are changing in the Great Lakes region now and into the future? And are changes happening faster in some areas of the Great Lakes than others?

Dr. WASHBURN. Thank you.

Yes. So the data and the models and forecasts are all showing across the Great Lakes more frequent and more intense storms, also changes in the precipitation patterns, as you alluded to, with more rain coming in the winter because what is happening is the winter temperatures are not as cold as they used to be. I think that in Wisconsin the projections are 5 to 11 degrees warmer in the winters in northern Wisconsin in the next 15 to 20 years. That is a really short time period. That is a substantial shift. So the forecasts and models are showing regionally the upper latitudes of the Great Lakes warming faster, but these precipitation and intense events happening off the normal seasonal cycle. That has implications for flooding. If your soil is frozen and you have snow melting or rain coming at a certain time and it cannot penetrate the soil, then you are going to have flooding in those areas potentially during part of the winter as well. So, yes, there are certainly issues around the Great Lakes on that topic.

I think the other thing that strikes me when I look at some of the data is the heat extremes projected for the region, something on the order of 2 to 5 weeks above 90 degrees in the same period in the next 20 years. That is substantial. That leads to all kinds of questions about vulnerable populations, about urban communities, and challenges to public health.

Senator BALDWIN. In dealing with these disasters, our communities are having trouble recovering and rebuilding to be safer and stronger in part due to limited resources, lack of resources, as well as the Federal assistance does not arrive immediately, as we know, in this process.

As a community leader—and I know you are a local resource to our coastal communities—I want to see if you can share what you are seeing in the aftermath of these events. What challenges are you hearing from the local leaders who are on the front lines of responding to these extreme weather events? And are recovery efforts providing lasting resiliency? Or if not, what are you hearing is needed?

Dr. WASHBURN. So on your last question, one of the challenges of Federal funding coming in response to these events, besides the length of time that it takes, is that FEMA will cover rebuilding up to the same design of a culvert, say, that was there in the first place. And what the communities need is to make their culverts and water infrastructure bigger to handle these events. So that is a challenge right there.

Community leaders are also struggling with communicating risk. One of the things we have not talked about yet as a community is how we are going to talk about warmer temperatures and algal blooms. We are starting to get questions, people walking in the door literally and asking what is going on out there.

But communicating risk related to these water levels and habitat and changing temperatures that is something that I think the local leaders and government needs to be supported by more. And we

can do that. The reserves have a wonderful system of risk management trainings, really fine-tuned after Super Storm Sandy with the Jacques Cousteau Reserve in New Jersey. But that can be rolled out across the entire system, which can benefit Superior and Duluth and the north shore of Wisconsin.

I think another challenge that we have learned is—and this is actually not related to a natural disaster flooding, but the Husky refinery fire. One of the things we learned is that the emergency management structure in western Lake Superior—it is not the same with necessarily the rest of the country, but in our region—does not include a standing body of scientists to respond with on-the-ground monitoring.

So one of the things that we talked about with our partners up in that area, and that we are starting to have conversations with the emergency management world, is can we coordinate the science experts in that region and be that point of connection to emergency management to try to get more of the on-the-ground science done post events, whether they are flooding or something else.

So there are a number of different things. There is risk communication. There is coordinating science and then working with communities on new kinds of communication about new threats.

Senator GARDNER. Thank you, Senator Baldwin.

I will give Senator Blumenthal a little chance to settle in because he is up to bat if you want to take the turn here.

I agree with the interaction you had on the issue of FEMA and some of the challenges we have in the western states as it relates to the forest fires and the flooding, a little bit different than other areas of the country might have. And so some unique challenges in how FEMA does their work and creates those aid opportunities. But a very good discussion I think we need to continue.

Senator Blumenthal, you are up next if you would like to spend a few minutes.

STATEMENT OF HON. RICHARD BLUMENTHAL, U.S. SENATOR FROM CONNECTICUT

Senator BLUMENTHAL. I am happy to proceed, Mr. Chairman.

In Connecticut, we face the kind of weather that has become the new normal, the super storms that demand resilience of our planning and our construction. I am going to hold up just one photo of the Connecticut shore that is the most visible sign of what happens. People think of super storms as happening in the Gulf, in Florida. But here is Connecticut, and that is what all of Connecticut's shoreline looked like after Super Storm Sandy. It was reduced to a super storm from a hurricane even though it hit with hurricane force along our coasts in many areas.

So my question is, do you think that Congress has to make the American public and also itself act to assure that there are sustainable investments as a result of this infrastructure program that now seems on the verge of happening? There is a lot of bipartisan support for infrastructure and, in fact, the Seventh Annual Infrastructure Week began on Monday. Negotiations are ongoing between President Trump and Democratic leaders. But how important is sustainability as a feature of this infrastructure initiative?

Dr. ABDALATI. So if I may. It is critically important. You know, you have scientists here. We understand the physical processes. We understand the manifestation. Policy is certainly your domain where you have to bring in a lot of information to make decisions. You have to consider the economic implications again of action versus inaction, and both have implications.

I had said in my opening remarks that our success as a society in the face of a changing climate, no matter the causes, depends on how big the changes are, how fast they occur, how well we can anticipate them, and how prepared we are to adapt to them. And the items you had touched on, you know, how big they are and how fast they come, those are mitigative measures and those require certain kinds of policy decisions or actions. I am not qualified to make recommendations in that area as I can only tell you what happens if we do not mitigate.

But to your point, adapting, resilience must be built into the thinking, otherwise that picture is going to occur over and over and over again. And that comes with cost in dollars. That comes with cost in lives. That comes with cost in health and safety. So I think it is absolutely critical that we as a nation and you as legislators build that into your thinking. I cannot tell you the degree to which you do what thing. But I can tell you that it requires being informed by sound science, of which there is plenty, and taking that in consideration of all the other variables and parameters that come into play and making decisions or making policy based on that. But absolutely the incorporation of resilience, because you are going to face those situations again and again, is critical I think to the success of coastal communities and the same is true in the interior of the country in response to other threats.

Senator BLUMENTHAL. Thank you.

Dr. BRONK. I wanted to add two points.

One, as we move into the future, one reality that I think the Nation needs to face is we are not going to be able to build all the places we used to build before and probably should not have built in many of those places to begin with.

And the second is when we rebuild areas that we rebuild in terms of the infrastructure, to look at not just what we will need now, not in 10 years, but in 50 or 100 years, and to invest in the development of new building techniques, new materials that are much more resistant and easier to manufacture, require less energy. And right now, one of the big gaps to getting those types of materials to market is going from the development phase all the way to getting it to market, which is kind of the trough of death, that if the Federal Government could look at that space, I think we could have a lot more solutions than we have right now to some of these types of problems.

Senator BLUMENTHAL. Thank you.

Yes, sir.

Dr. HORTON. Thank you.

You know, clearly the statistics of many types of extreme weather events have already shifted, whether we are talking about heat waves, heavy rain events, or the frequency and intensity of coastal flooding. I think I am on less firm ground talking about the age of some of our infrastructure, but to the extent that an infrastructure

anyway would need repair just to sort of maintain a baseline, that is an additional argument beyond this argument of the shifting statistics of extreme weather for new infrastructure that is more resilient. Of course, there are co-benefits probably—many co-benefits for sure—of these types of infrastructure investments.

I like the way you frame this around the sustainability issues, though, because I think we do need to think about the combined greenhouse gas mitigation components and greater resilience aspects that we can get through infrastructure investment.

And to give one example of this, we are starting to hear in the context of this notion of managed retreat, that there are some parts of the country where we hear more and more it may not be possible to continue to invest on resilience in place. There may be health risks in terms of greater challenges of evacuation in the future. So that dialogue is beginning I think to well up. And infrastructure is a critical part of that. Right? You are starting to hear a little bit in some cases about sort of moral hazard maybe of infrastructure investments in some of those most vulnerable areas. In another context is some of the ability to fund some of that infrastructure potentially going to change in the future if we see some changes in asset values, as some of these risk perceptions are appreciated?

So it is a complex space, and I think the kind of forward-looking perspective on infrastructure that considers those climate hazards and considers the interaction between greenhouse gas mitigation and adaptation could be really productive.

Senator BLUMENTHAL. Thank you.

Senator GARDNER. Thank you very much.

Dr. Washburn, quickly if you would. Did you want to respond to that?

Senator BLUMENTHAL. My time is expired I know, Mr. Chairman.

Senator GARDNER. Yes, but if she would like to respond, please feel free, quickly.

Dr. WASHBURN. Just very quickly. I would frame things through resilience more than sustainability. I think that is community, that is economics, that is social resilience as well. And I think that framing gives you more latitude to explore some of these challenges about moving things and migrating communities, coastal wetlands, et cetera.

Senator BLUMENTHAL. Well said. Thank you all for this very articulate and important hearing. And I want to thank the Chairman and Ranking Member as well for focusing on it. Thank you.

Senator GARDNER. Thank you, Senator Blumenthal.

Dr. Abdalati, we are going to go another round here. I apologize if you thought you were going to get out early.

Dr. Abdalati, you mentioned improvements to drought forecasts and forecasting smoke plumes in your comments. Will those models some day be able to forecast drought accurately enough to adjust agriculture, fire fighting plans, those kinds of things?

Dr. ABDALATI. I believe they will. I guess kind of not to parse here, but it depends by what you mean by address because I think they are already being taken into consideration in the context of farming practices. The ability to grow things is changing. In fact, interestingly when you, again, remove the political discourse or the

political element out of the discourse and you talk to rural farmers from your former district when you were a Congressman, they get it. You know, they understand climate is changing and that they cannot grow things in the way they used to. And I think there is a critical need, and I think we are progressing toward that need to be able to tell the farming community what they are looking at in the seasonal/sub-seasonal domain and perhaps even years down the road. You know, as the climate has warmed, sort of the isotherms, the temperature lines have moved northward, you know, the average temperature. The same is true with moisture. It has changed in a changing climate.

So certainly the models are doing a pretty good job of characterizing and predicting drought. There is a ways to go. One of the nice things about NIDIS, which interestingly was reauthorized during the shutdown, which was nice to see, is that it seeks to pull together all the information that we have from State sources, from universities, from Federal sources, provide that in an integrated way. That is the second "I" in NIDIS I think. So it already draws from what we have in ways that are useful.

And it does come back too, though, to the social science domain. It needs to be communicated in a way that people will use and understand. But it is certainly within our capability. Substantial progress has been made, and I would expect, with continued investment, it would continue to move forward.

Senator GARDNER. Very Good. I remember the roundtable we had at the University of Colorado talking about social science and the impact that it had.

In terms of forecasting capabilities, are you getting the cooperation you need from Federal research partners? What more can we do to bolster those Federal partnership efforts?

Dr. ABDALATI. So we are. The nice thing is everybody is working toward the same goal, the same outcome. I do think in the case of NOAA, there are efforts to integrate the activities of the National Weather Service and the Office of Atmospheric Research, NWS and OAR. And I think more of that would be helpful. There are efforts underway at NASA for data assimilation of the satellite data to improve forecast capabilities. It is how do we integrate the data into the models. I think all of the entities are working toward that outcome.

I would say sort of like through the Weather Act, setting a clear goal of where we need to be and telling agencies this is the direction you are working toward has been and will continue to be productive.

So I do not have specific recommendations, you know, if only you could get NASA to do this. I used to be Chief Scientist at NASA. So I had my chance. But I will say just in a general sense, every entity, Energy, NSF, NASA, NOAA plays a role in the research to operations and operations to research domain, and I think they are well structured to interact.

One thing I do want to comment on—and I am sorry for the time, but there is something called EPIC, and I am forgetting now what it stands for. But it is the integration of activities at NOAA and NCAR, the National Center for Atmospheric Research, which is NSF-funded, really bringing together the best of both in the re-

search and operational domains. And I think that is really something—that is a big step forward that is in process—that is going to move the ball down the field in reasserting our leadership in weather forecast and weather prediction.

So efforts are underway. Everybody wants the same thing. I think the best way the government and legislation can facilitate that is by setting the clear goals and requiring that everybody play nicely in the sandbox together, which I think they do.

Senator GARDNER. Thank you, Dr. Abdalati.

A quick question. When you look around the globe and you see other countries that are investing, you know, are other people leading our investments or beating our investments in space research, space applied research, those kinds of things that you need to do this job?

Dr. ABDALATI. I would say they are not beating our investments. There have been investments in forecasting in Europe that have been quite substantial and have really moved the ball down the field for them. In space observations, I think the United States continues to lead the way, but we used to be the big thing, and JAXA, the Japanese space agency, the European Space Agency, India, others have really stepped up and have been contributing. And what is nice about that is all nations benefit through the sharing and open access of data. So I would not say we are being surpassed in these areas. I will say we are being approached in these areas. But ultimately I think it is for the benefit of society as a whole.

But continued investments in these observations—and as I said, I co-chair the decadal survey—are absolutely critical for the success of our Nation with regard to climate, weather, earthquakes, drought, you name it. We have got to watch the story unfold to test our models and understand what is happening and why and where it will lead us.

Senator GARDNER. Thank you, Dr. Abdalati.

Senator Sullivan.

STATEMENT OF HON. DAN SULLIVAN,
U.S. SENATOR FROM ALASKA

Senator SULLIVAN. Thank you, Mr. Chairman. Good to see you in the chair on this important committee.

I want to thank the witnesses.

I am going to ask a couple questions that relate—and I know I am going to be a little bit off topic, but we got so many smart people in terms of our witnesses that I am just going to throw these two questions out that deal with the sustainability of our oceans.

So my state, Alaska, in terms of commercial fisheries and recreational fisheries, we constitute—almost 60 percent of all the seafood harvested in America comes from Alaska's waters. I like to use the term "super power seafood."

But anyway, making sure that we have sustainable fisheries whether in the Great Lakes or in Alaska or all over the world is I think something that this committee takes very seriously. It needs to be focused on data. I think a lot of people view the Alaska North Pacific Fisheries Council model as part of Magnuson-Stevens is probably one of the best managed fisheries in the world. And so we take it very seriously.

So two questions that I wanted to ask related to this. One is the issue of ocean pollution, in particular the issue of plastics. And Senator Whitehouse and I had a bill last year called the Save Our Seas Act that was signed into law by the President, and it is an area where there is good bipartisan cooperation. Democrats, Republicans, the Trump Administration, environmental groups, industry starting to focus on this, which is important.

We are going to introduce a bill here in the Commerce Committee soon called the Save Our Seas Act 2.0. But I am wondering if any of you have any thoughts on addressing the challenges that we see in terms of ocean debris, plastics, ocean pollution. If it is not in your area of expertise, I apologize. But there are a lot of smart witnesses here, and I thought I would put that on the table because it is a very important issue. And there is a lot of bipartisan momentum to address it, and I think that is important and we need to keep that going.

Dr. BRONK. So I am an oceanographer, so thank you very much for that question.

Senator SULLIVAN. Yes. I was going to ask you directly, but——

Dr. BRONK. So ocean plastics—I do not have a good answer for you on how——

Senator SULLIVAN. The estimates, just by the way, are five countries, 10 rivers in Asia constitute almost 80 percent of all the plastic pollution in the world. So it is a solvable issue, very solvable. We know who the source is.

Dr. BRONK. I know one thing we could do is we could not have one of these sitting next to each one of us. I know I opened mine. I am sorry. And I am drinking it.

So ocean plastics—I mean, it is a real issue. Investing in research on how to deal with it—and yet, what most people do not understand is that the plastics that we see, the bottles on the beach, the fishing rope, that is probably 1 to 10 percent of the plastic in the ocean. The real problem of plastic in the ocean are micro or nanoplastics that we have very little information on.

Senator SULLIVAN. They are starting to show up in the food chain. Correct?

Dr. ABDALATI. They are showing up everywhere. Right.

We had a researcher, Patty Matrai, at Bigelow who studied microplastics, fibers in mollusks and mussels. And it turns out how these organisms deal with the plastic is they create pseudo-feces. So they package this up kind of in mucus and then put them out of their body. The good thing is it gets the plastics out of the body before you eat them. The bad thing is that is a very energetically expensive thing for a mussel to do, and that is going to cost you money if you are raising mussels. And so we are doing research—and it needs to be expanded in a number of other places—on how to deal with this in our seafood, how to get as much of the plastic out of the seafood as we can before people eat it.

But the micro and nanoplastics—I mean, we really do not even have good techniques on how to count them. Right now, you use a hot poker in a microscope and pick them up one piece at a time. So finding automated techniques on how to accurately monitor them so we know where the concentrations are highest, where are they lowest, where do we need to focus our efforts. And then I have

no good answer, and I have never heard of any good answers on what we do about them once they are in the ocean.

So stopping the flow into the ocean and investing in—I think we need real innovation, real out-of-the-box thinking on managing plastics going into the future.

Senator SULLIVAN. Well, that is going to be in large part in our bill.

So, Mr. Chairman, I look forward to working with you and the Ranking Member on this issue, and hopefully we will be able to get some momentum on that.

And, Dr. Bronk, thank you, and if you have any other thoughts on this—you or your colleagues who focus on the ocean sciences—please let us know.

Dr. Washburn.

Dr. WASHBURN. Yes. I just wanted to add to that.

So microplastics are a huge topic in the Great Lakes. And one thing I would urge you to consider is some way of structured funding for wastewater treatment research and development to be able to find microplastics in wastewater treatment plants and pull them out.

We are in a matter of days taking researchers from the University of Wisconsin-Superior out onto Lake Superior and in the estuary to sample for microplastics. It is something we have been doing for years. Sadly, it is showing up in most if not all of the beer produced in the Great Lakes, which is tragic for a lot of reasons. But it is in everything now. And so I would just reiterate the microplastics are huge.

NOAA has a marine debris plan that is regionally based, and I know a lot of the other reserves are plugged into that. We help support the research and education about plastics, both large and microplastics. So that is something we are doing up in your state too, I believe.

Senator SULLIVAN. Great. Thank you very much.

Thank you, Mr. Chairman. Oh, anyone else on this?

Dr. HORTON. Thank you. Yes, just to maybe extend this a little bit but hopefully still relevant. I think another of these complex problems in the context of fisheries, the interaction of increasing ocean acidification, changes in oxygen rates, which vary a lot but are changing around the ocean, and then especially the increase in the ocean temperatures. I am thinking specifically, for example, about Arctic sea ice where in that sort of late summer/September volume, we have seen a 50 to 75 percent decrease in the past 40 or 50 years in the volume of that Arctic sea ice. It takes an enormous amount of energy to happen. And I think there is a lot we really do not know yet about what that is going to mean for fisheries, about how that is going to impact and relate to changes in ocean circulation. So it is one of these sort of unknowns but another example I think of where the further we push the system, the bigger the potential for surprises that we need to think about as we are considering some of these related hazards.

Senator SULLIVAN. Thank you, Mr. Chairman.

Senator GARDNER. Dr. Abdalati.

Dr. ABDALATI. Yes, just very quickly. The plastics is an example of the kinds of greater problems we face. We have the plastics prob-

lem for reasons of convenience and short-term economics. That is why we use plastic. It is economic. It is convenient. People like it. People make money when they can access bottles of water quickly.

It really comes down to—and this is the same as the broader climate question—how do we value tomorrow versus today. We are creating problems for the future so that we can benefit today. And again, I do not know the answer there, but there is a common thread through this, through climate change, through ozone, all of these kinds of things. We have these challenges because they are economic and convenience offerings in these today but come at a price tomorrow. And that is just the balance. And tomorrow is today.

Senator SULLIVAN. Thank you, Mr. Chairman.

Senator GARDNER. Senator Baldwin.

Senator BALDWIN. Thank you.

I want to try to put out some recap questions and hopefully also draw this hearing to a close on an uplifting note. But let me start with the recap.

A number of you in your testimony talked about the data gaps that exist that hold us back. And I do not want you to repeat your testimony now, but it would be really great perhaps as a follow up to this hearing if you can just sort of identify the biggest data gaps in your expertise and help us think about how the Federal Government plays a role in helping you close those gaps.

I want to dovetail on the issues we have been talking about relating to communication to the people who need this information and outreach and educational opportunities and not so much from the standpoint of what we have not done, but what has been working. I am going to, as usual, pick on Dr. Washburn first because the reserve is a place of outreach and education. A lot has been done. Tell me what you think is working in terms of public education about our changing climate and changing circumstances on Lake Superior and the estuary.

Dr. WASHBURN. Sure. Thank you.

So in terms of outreach and education to the public to help people understand what is going on, one of the highlights from our area is the annual St. Louis River summit. We have been hosting that at UW-Superior for 9 years now. It draws—actually we are at fire code limit now—300 people for 2 days and it is all of the research monitoring going on across all kinds of different fields in western Lake Superior and beyond. It is getting so big, as a matter of fact, that we are thinking we might have to expand to an actual conference center elsewhere. So that is a good thing. There is a lot of interest in it. So the St. Louis River summit is one of our highlights.

I will also say that we do a lot as one of the eight university lab reserves. We do a lot with students with actually some high school students but a lot with undergraduate students and grad students. With the new reserve Margaret Davidson Fellowship, we will have additional workforce capacity and training that we will be able to bring to bear across the system. So I am excited about that.

And one example I think—there are two examples really quick. One I mentioned in my testimony about algal blooms. We are really concerned about that, and our coastal training program coordinator

is working with partners across the south shore of Lake Superior to figure out how can we develop a monitoring strategy starting this summer every 2 weeks to go out and sample for algal populations in the near shore. That is going to draw I know a lot of media and attention, and we are going to be getting the word out about that.

And then kind of bringing it home to habitat and to some of our core work, one of the areas that we have—our sentinel site, climate change station is Pokegama Bay. And some of the work that we are doing there involves this invasive species called emerald ash borer, which is decimating ash forests in the upper Midwest. And we have long-term research plots there to see what kinds of species of trees can communities plant that can stabilize the sediment in these riparian areas and help the forest recover from the loss of ash trees. That kind of long-term research tied with our system-wide monitoring program is something that we are positioned to do really well, and the benefits from that will be shared with public and private landowners who want to manage their forests for the future.

So those are some examples.

Senator BALDWIN. Great. Thank you.

Anyone else? Please.

Dr. ABDALATI. With regard to data gaps, I would say satellites—you know, my own expertise—have played a critical role in our success in understanding our changing environment. There is a road map that has been provided by the National Academy's decadal survey for NASA, NOAA, and the U.S. Geological Survey, and we were very respectful of budget limitations. So I think the implementation of that would go a long way.

With regard to what works, I think what works is the way we talk to people. I actually have a TED Talk on communicating controversial topics, and my main principles are, one, your adversaries are not as dumb as you want them to be.

[Laughter.]

Dr. ABDALATI. They are sort of like if you just understood things, you would see it my way.

Another is framing ideas in ways that resonate. When I talk about climate change with rural farmers, I talk about the implications for farming.

Recognizing values that people do not come to what they believe because they are not smart. They have certain values. They may value some things in different ways than I do and vice versa.

And the last is not telling people what to think. That is just the worst thing you can do.

And so I think dialogue that is really open-minded—what can I learn from you, not I am the scientist, I have something to tell you—goes a long way. People feel when you are sincere about moving forward. So I would say what works is constructive engagement that respects different values and ethical principles.

Dr. BRONK. So in terms of data gaps, when it comes to the ocean, they are huge. And part of the problem is up until maybe 20 years ago we really were sampling the ocean from ships, or satellites were a huge boon for ocean science. You still had the ground truth those satellite measurements with ships.

So now we have a variety of different platforms, including floats, which are basically tubes that slowly move up and down the ocean. They have got basically a cell phone in them, and when they hit the surface again, they beam the data that they have collected and their location. It is an Argo float program is the program that is just wonderful. It is an international program. There are 3,800 floats out purchased by 34 different countries. And it is an example of how ocean science is starting to fill some of the data gaps.

But the problem is most of those floats only collect temperature and salinity, and that is not enough. We need all the biological variables, chemical, you know, what are the different chemical constituents, nutrients, all the things that control how fast the phytoplankton grow at the base of the food web, what types of phytoplankton are out there. That is going to tell you how far up you have to go till you get to a fish that you could commercially harvest.

So what we have right now is fantastic compared to what it was 20 years ago, but it is still a very rudimentary system. So investment in developing the sensors to put onto these floats would be fantastic.

And the other thing I wanted to call out—and this is from my time at the National Science Foundation when I was always fighting for funding for ocean sciences, and yet what I was consistently seeing was my social science colleagues just kind of getting hammered. And yet, the number of times social science has been brought up in these discussions—it is at the root of so much of how we will respond to climate change that this country really needs to invest in really some fundamental basic research on how we can help people adapt and understand how they will behave and their behavior will change because—my oceanography colleagues are going to be like what are you doing. But I think as a country, we really need to invest in social science research because that is going to drive how we respond as a nation to a lot of these challenges.

Senator GARDNER. Thank you, Dr. Bronk.

Dr. Horton, if you do not mind, we will get to Senator Udall real quick and then maybe you can follow up with him.

Senator Udall.

STATEMENT OF HON. TOM UDALL,
U.S. SENATOR FROM NEW MEXICO

Senator UDALL. Thank you, Mr. Chairman.

Dr. Abdalati, your research focuses on the Earth's polar ice cover, and obviously, I am from New Mexico, a landlocked state. You are from Colorado, the Chairman's state, which is the same situation. Why should people from New Mexico and Colorado be concerned about the impacts to polar ice cover and why is the Arctic so important to the planet? Just a brief answer there because I have a couple of follow-ups.

Dr. ABDALATI. Sure. Well, first of all, as citizens of this nation, I would hope we would care about what is happening to our fellow citizens in coastal regions not only from a humanitarian perspective but also economic. That has implications for the economic wellbeing of our country.

From the standpoint of what directly hits home in New Mexico and Colorado, it is a little bit more removed, but in the simplest sense, human civilization has not known a seasonally ice-free Arctic Ocean ever. And so we are taking a sledge hammer to the climate system. When we peel back that ice, which traps heat in the ocean, that heat is released to the atmosphere, changes atmospheric circulation, and ultimately impacts weather and precipitation patterns all over the world. So the disappearing Arctic sea ice cover ultimately I believe and many of my colleagues do has implications for the weather in Colorado and New Mexico, the potential for extreme. We are putting more water vapor in the atmosphere. We are releasing more heat from the ocean into the atmosphere. That perturbs the global climate system. So it is the opposite of Vegas. What happens there does not stay there. It actually propagates worldwide.

Senator UDALL. Very well put.

Since you study the Arctic, you probably saw what happened at the recent meeting of the Arctic Council. The first sentence of the "New York Times" story about it reads—and I am quoting here—under pressure from the United States, the Arctic Council issued a short joint statement on Tuesday that excluded any mention of climate change.

But that was not all. Our Secretary of State Mike Pompeo said, quoting here, steady reductions in sea ice are opening new naval passageways and new opportunities for trade. And he added, Arctic sea lanes could become the 21st century Suez and Panama Canals.

Do you or any other panelists here think that melting Arctic ice is opening up new opportunities that are a net benefit to people of this country or of the world?

Dr. ABDALATI. Oh, I believe melting Arctic ice is opening up new opportunities. We cannot deny the opportunities that are presented. The question is, is it worth the costs that come with it?

The military is concerned about the implications of activity in the Arctic and what that means for our national security. The climate implications and weather implications can come at tremendous economic costs. As the sea ice melts and exposes the shipping routes, which will save lots of money and create opportunities, so too is the land ice melting, which is causing oceans to rise, which is having tremendous impacts in coastal regions.

So I sometimes challenge my community that we tend to not think about opportunities. There are opportunities with the change in climate, but there are costs. And it is the opinion of most in my community that these costs and these perturbations—and I strongly share this—far outweigh the opportunities associated.

But it is incumbent upon us to understand these changes, I often say, so we can meet the challenges and capitalize on the opportunities that they do present.

Senator UDALL. Do any of the other panelists want to weigh in on that?

Dr. HORTON. Just to add a couple more additional examples.

So we heard there about how loss of Arctic sea ice can have impacts on regional climate that extend to many different areas. We heard also how it can interact with the land-based ice, leading to interactions that could potentially increase both the melting of that

ocean ice and the land ice, maybe even impact broader ocean circulation.

Another point to highlight is that the basic climate sensitivity of the planet, which is essentially for a given amount of greenhouse gas that we add to the atmosphere, how much will the planet as a whole warm. Changes in Arctic sea ice have some potential certainly to partially accelerate that sensitivity. So you remove that very reflective ice surface and now have ocean underneath, a dark surface that can absorb more sunlight, it sets off a powerful feedback that then can melt additional ice. You add more moisture to the atmosphere. That is a water vapor feedback that, to some extent, is going to give you some more warming. So there are uncertainties there.

But even beyond the sort of regional implications, sort of the basic sort of physics of how much the planet could warm for a given amount of increasing greenhouse gases and potentially longer term even a feedback where the very amount of greenhouse gases could potentially go up a little more as you warm some of that land surface, melting permafrost. That is probably not a rapid feedback, but it is an additional thing to think about that could make us a little less the arbiters of future greenhouse gas concentrations if we are not careful.

Senator UDALL. Mr. Chairman, with your permission, can the additional panelists just finish answering the question? Thank you.

Dr. BRONK. So I have done nine trips up to Barrow, Alaska, Utqiagvik, Alaska, where I went out onto the sea ice to drill through to sample the ocean. I think my first trip up was in 2012, and since that time, the loss of sea ice, which is very protective of the coast—if you have got sea ice in the winter and farther into the spring, later into the spring, it protects the coasts from these storms that come in. Well, now that the sea ice is gone earlier in the year, it is just devastating the community in terms of erosion. I am sure the road that we used is probably gone now. I have not been up there for 2 years, and I am sure it is gone. The rate of the erosion and what the town will do, I do not know.

So, yes, there will be positive things with an ice-free Arctic, but there is also going to be just devastation to a lot of the communities up there.

Senator UDALL. Did you want to say anything?

Dr. WASHBURN. Yes.

So in the Great Lakes we, of course, are not talking about sea ice but lake ice. We have seen a four-decade decline in the extent of coverage of all five Great Lakes in the winter.

Likewise with the marine system, we are having conversations with people in the shipping industry who see that as an opportunity for a longer shipping season, getting out earlier in the year and coming back later.

But it is also contributing to complexities in understanding lake level change in the Great Lakes. The open water—there is more evapotranspiration year round. That is leading to a more difficult situation to understand the interaction between lakes, precipitation, groundwater, surface water. And that is going back to my original testimony of how hard it is for coastal communities to plan

for the kinds of precipitation events and flooding that might occur under a really complex lake level change scenario.

So we are not dealing with sea ice, but similar conversations.

Senator UDALL. Thank you for the courtesies, Mr. Chairman.

Senator GARDNER. Thank you, Senator Udall.

And thank you to all the witnesses for being here today. I want to thank our colleagues for participating in the hearing.

The hearing record will remain open for two weeks. If members have questions for the record, I would kindly ask the witnesses to do your homework, if you could, quickly and get it back. Questions and answers will be included as part of the record. So thanks to all of you.

And with the thanks of this committee, this hearing is adjourned.

[Whereupon, at 11:30 a.m., the hearing was adjourned.]

A P P E N D I X

RESPONSE TO WRITTEN QUESTIONS SUBMITTED BY HON. RICHARD BLUMENTHAL TO DEBORAH A. BRONK, PH.D.

Issue No. 1: Need for Immediate Legislative Action on Climate Change. The consequences of global climate change are devastating and far-reaching, and both immediate and long-term. Climate change threatens our economy, our national security, our beautiful natural places, and even our lives. Still, Congress delays meaningful action on combating the worst effects of climate change. For residents of my home state of Connecticut, facing climate change is not a choice. Superstorm Sandy claimed 147 lives and cost billions of dollars in damage. Scientists predict an almost two-foot increase in the sea level of Long Island Sound by 2050, meaning that smaller storms could result in greater flooding. My constituents simply can't wait any longer for the United States to take action.

Question 1. Do you agree that it is critical that the United States Senate consider and pass legislation to address climate change this Congress? [Yes or No]

Answer. Yes. We have delayed for far too long already.

Question 2. Given the expansiveness of climate change and its effects, what mechanism or strategy do you believe Congress should prioritize when considering effective climate change solutions?

Answer. We need an integrated approach. To successfully address climate change, we must consider societal, behavioral, economic and environmental issues together. One problem is that experts in these fields seldom talk and collaborate—they too often exist in their own silos. The National Academies runs the most rigorous, unbiased scientific review and planning process I know. Support them to develop a national strategy and underpin it with substantial funding to implement through the Federal and state agencies. There are already a number of National Academies reports, a few noted in my written testimony, that can be turned to for guidance on how to move forward on many issues today.

Underpinning all of this is the need for a true valuation of the cost of U.S. activities. For example, it would be cheaper for a given industry to send pollutants into the air, but if you include the increase in health care needed to treat the many health problems those pollutants caused, it makes economic sense that our government not allow them to do so. Likewise, industry and individuals need to make decisions based on the true cost of their activities with respect to greenhouse gases. Taxing carbon will provide an economic incentive for looking critically at how we live and the energy needed and the waste generated. This economic incentive will power innovation and new approaches will be found. A critical component to this approach is the monitoring needed to assure compliance.

Last but not least, we desperately need political reform to limit the power of special interest groups. How different our world would be today if powerful, well-funded lobbyists hadn't been able to squash innovation in fuel efficiency, for example.

Question 3. Connecticut residents are already facing the consequences of climate change. How can the United States Northeast ready itself for a warmer world?

Answer. People need resources to transition to a more sustainable lifestyle. Options include low interest or no interest loans or subsidies to transition to green energy. There are homes on the coast in the Northeast that are on land that should not, and in many cases, should never have been, built on. As storms worsen and sea level rises, we need a robust plan to transition to more sustainable coastal properties that don't leave the tax payers holding the bill for rebuilding these properties after repeated floods or water damage.

Issue No. 2: Fostering the Necessary Paradigm Shift to Mitigate Climate Change. This year, two landmark studies were published that document the extent of climate change's impacts on humans and the planet—the Fourth National Climate Assessment and the Global Assessment Report on Biodiversity and Ecosystem Services. Both reiterate in great detail what we have known for decades: climate change is

real, humans are causing it, and we must act boldly now. These reports note that our options to mitigate the worst effects of climate change—through domestic policies and international agreements—are insufficient to meet the scale and rate of our changing climate. We need "fundamental, system-wide reorganization across technological, economic, and social factors, including paradigms, goals, and values."

Question 4. How can Congress foster the fundamental, transformational changes needed to save human lives and biodiversity in the face of powerful opposition and inertia?

Answer. We have to level the playing field. I support comprehensive campaign finance reform. Let decisions be based on science and the will of the people, not a small number of wealthy individuals or industries. Also, support citizen science programs. The financial investment is nominal but could allow this country to collect many types of data that would be cost prohibitive if it had to be done by professionals. The added benefit is that involving citizens in the collection of environmental information will educate them on the issues and empower them to support wise stewardship of our resources.

Issue No. 3: The Need to Invest in Sustainable Infrastructure. As Congress considers a major infrastructure package, we cannot ignore the risks of climate change. Fundamentally new approaches to infrastructure investment are needed, including a focus on clean energy transportation, efficient travel, grid upgrades, and sustainable materials and design. In addition to ensuring that the built environment helps instead of harms humans and the planet, Congress should invest in green infrastructure, including healthy natural spaces. Connecticut's state economy is reliant on the myriad ecosystem services provided by coastal ecosystems, including estuaries, marshes, and open water. I would like to make Connecticut home to the thirtieth National Estuarine Research Reserve (NERR), and I have led efforts to encourage the National Oceanic and Atmospheric Administration to move quickly to approve the proposed Connecticut Reserve. Mitigating climate change's effects on green, blue, grey, and other types of infrastructure is essential for our health and wealth, and deserves Congressional attention.

Question 5. What are some of the most important investments that we can make to ensure our Nation's infrastructure is more resilient or adaptive to the variety of hazards posed by future climate conditions?

Answer. Support robust climate modeling and forecasting at the national and regional level. Models are our most powerful tool in understanding how our environment is likely to change but they have never been financially supported at the level needed to answer the questions we face. Then we need programs that support two-way communication between the modelers and scientists creating these programs and the local and regional managers that will use them to make decisions. A closer relationship across this spectrum will inform modelers of the most pressing issues and the type of information needed to address them and educate local and regional managers on model limitations and data needs.

Question 6. How does the preservation of coastal habitat—such as those in the NERR system—help mitigate the effects of climate change on infrastructure?

Answer. Marsh, mangroves, coral reefs and barrier islands all protect the land that lies behind them by dissipating energy from wind, waves, and water during storms. For example, filling in marshes and building on them has created vulnerable low-lying land and removed valuable protection for the inland communities adjacent to it. It has also eliminated space for water to go during storm surges without damaging infrastructure because homes are now built where the marsh used to be. Preservation and restoration of these natural protective barriers should be part of any plan to protect our coastal communities going forward.

RESPONSE TO WRITTEN QUESTIONS SUBMITTED BY HON. EDWARD MARKEY TO DEBORAH A. BRONK, PH.D.

Question 1. What Federal investments and/or initiatives are necessary to support the sustained ocean and climate observations and modeling needed to fill our gaps in climate understanding?

a. Are there existing programs that should be supported or expanded?

b. Are there new programs or partnerships that should be created?

Answer. The answer is yes to both. To assure that investments are impactful and cost effective, a critical first step is establishing a long-term plan for ocean observations.

To address both of the questions, I direct the senator's staff to the following report noted in my written testimony and have copied an excerpt of the Summary that directly addresses this issue:

National Academies of Sciences, Engineering, and Medicine. 2017. *Sustaining Ocean Observations to Understand Future Changes in Earth's Climate.* Washington, DC: The National Academies Press. *https://doi.org/10.17226/24919.*

NATIONAL COORDINATION, PLANNING, AND FUNDING CHALLENGE

Although the interagency bodies described above have responsibilities to coordinate activities associated with ocean climate observing, the committee has not been able to identify a clear national leadership position for this intersection of ocean, climate, and observing. Neither has the committee been able to identify a national plan to sustain and expand this critical ocean observing system for climate change. Although Congress recognized the need for sustained ocean observations in the ICOOS Act, the annual budgets have not matched the costs of sustaining the current system in terms of workforce, infrastructure, and data management. *The absence of an overarching long-term (e.g., 10-year) national plan with associated resource commitments and lack of strong leadership presents a challenge for sustaining U.S. contributions to ocean observing, by inhibiting effective coordination and multiyear investments in the many components of the observing system.*

Finding: The continuity of ocean observations is essential for gaining an accurate understanding of the climate. Funding mechanisms that rely on annual budget approval or short-term grants may result in discontinuity of ocean climate measurements, reducing the value of the observations made to date and in the future.

Conclusion on Planning: Because of the extended time frame required for climate observations, a decadal plan for the U.S. ocean observing system would be the most effective approach for ensuring that critical ocean information is available to understand future climate. Consistency of the decadal plan with the Framework for Ocean Observing would optimize U.S. investments relative to contributions of the international community, with plan updates likely required to align with international activities during the 10-year period. Elements of a decadal plan include identification of requirements, assessment of the adequacy of the current system, components to be deployed over the 10-year period, potential for technological advancements, and an estimate of resources necessary to implement the plan. The National Ocean Research Leadership Council (NORLC) has the mandate under the ICOOS Act to oversee development and adoption of a long-term plan and NORLC could be responsible for its periodic assessment and update, possibly utilizing the IOOC and the Ocean Research Advisory Panel. Progress in implementing the plan would depend on the engagement of the broader stakeholder community and coordination with international partners in the global ocean observing system.

Conclusion on Partnership: An Ocean–Climate Partnership (OCP) organization described further in Chapter 5 would be an effective mechanism to increase engagement and coordination of the ocean observation science community with nonprofits, philanthropic organizations, academia, U.S. Federal agencies, and the commercial sector. Through their shared interests in the observational data and associated products, the OCP members could work together toward the goal of sustaining the ocean climate observing system.

Question 2. How can Congress help ensure that climate science is fully funded, especially to forecast local impacts that allow communities to prepare and respond to disasters?

Answer. As I noted above, we need to support robust climate modeling and forecasting at the national and regional level. Models are our most powerful tool in understanding how our environment is likely to change but they have never been financially supported at the level needed to answer the questions we face. Then we need programs that support two-way communication between the modelers and scientists creating these programs and the local and regional managers that will use them to make decisions. A closer relationship across this spectrum will inform modelers of the most pressing issues and the type of information needed to address them and educate local and regional managers on model limitations and data needs.

Question 3. How has the Trump administration's attitudes and directives regarding climate science affected your work and the scientific community?

Answer. For the leader of the country with the largest per capita greenhouse gas emissions to be a climate change denier is terrifying to anyone who knows what's at stake. It is also demoralizing that the leader of this great country is so ignorant and misinformed on the great challenge of our time.

Science is also an international activity that was largely led by the United States. The Trump administration has been devasting to our global reputation and leadership in science. In terms of long-term impact of Trump on how we will address the climate challenge, my most immediate concern is immigration. The United States was a science and innovation leader because we welcomed the best and the brightest from around the world. We brought people from different backgrounds and cultures and perspectives, who think differently and so expanded what we could have ever done alone. Now we are making it harder and harder for students to come here and to stay once they are trained. This is all happening at the very time that China is opening its arms to the world. I want the best and the brightest here. I want their brainpower and passion serving our republic as we tackle climate change. We need them.

RESPONSE TO WRITTEN QUESTIONS SUBMITTED BY HON. RICHARD BLUMENTHAL TO ERIKA WASHBURN, PH.D.

Issue No. 1: Need for Immediate Legislative Action on Climate Change. The consequences of global climate change are devastating and far-reaching, and both immediate and long-term. Climate change threatens our economy, our national security, our beautiful natural places, and even our lives. Still, Congress delays meaningful action on combating the worst effects of climate change. For residents of my home state of Connecticut, facing climate change is not a choice. Superstorm Sandy claimed 147 lives and cost billions of dollars in damage. Scientists predict an almost two-foot increase in sea levels around Long Island Sound by 2050, meaning that smaller storms could result in greater flooding. My constituents simply can't wait any longer for the United States to take action.

Question 1. Do you agree that it is critical that the United States Senate consider and pass legislation to address climate change this Congress? [Yes or No]

Answer.

- Yes.

Question 2. Given the expansiveness of climate change and its effects, what mechanism or strategy do you believe Congress should prioritize when considering effective climate change solutions?

Answer.

- Congress should consider convening a broadly representative Commission on Climate Change Adaptation tasked with drafting and proposing the funding priorities and national policy framework required to support mitigation and adaptation efforts across the Nation. Much of the needed work concerning the development of a vision, stakeholders and leaders involved, adaptation practitioners, and public and private sector roles and engagement are outlined in detail elsewhere, for example, in the comprehensively written *Kresge Foundation Report, "Rising to the Challenge, Together."* This is attached as an appendix to this statement.
- In sum:
- Adaptation work should include the development of an adaptation vision and practice, the identification of shared values, and clearly articulated priorities that are regional, sectoral and cross-cutting in nature.
- Reaching this vision and implementing this practice will require funding for knowledge generation and transfer, skill development and tools that the Nation as a whole can deploy to meet adaptation goals.
- The mechanisms to be developed include but are not limited to best practices for information sharing, learning, collaboration, advocacy and communication. These mechanisms and practices must be deployed at all scales and in all communities.
- A national policy and funding framework should be directed from national to regional scaled efforts, be based on the best available science while continuing to make critical research investments, and provide Federal agency directives to engage.
- A funding framework should be institutionalized so that resources and investments are coordinated and sustained. Critically, any strategy should involve innovation in technology, private investments and extensive cost sharing among

all the stakeholders benefiting from risk reduction. Identifying zones of shared risk is critical to both the evaluation of the effectiveness of strategies, and identifying beneficiaries. Negotiation of the best strategy and getting agreement on cost sharing is a difficult process and Federal funds should be used to incentivize stakeholder participation.

- The Commission must specifically include plans to address non-urban areas and socially vulnerable populations including the poor, elderly, communities of color and indigenous communities, focusing efforts on building social cohesion and equity. This is in recognition of the fact that communities of color, the socioeconomically challenged, and the rural areas or small towns will continue to bear the brunt of climate change impacts and the challenges of effectively engaging in an adaptation strategy.

Additional and specific mechanisms and actions:

- Reinvigorate successful efforts like the State, Local and Tribal Leaders Task Force
- Improve access to and use of important Federal data and tool portals to help communities understand, prepare for and adapt
- Continue investments in research to management on the ecological and economic impacts of green infrastructure as strategic solutions
- Strengthen support for the practice of ecosystem service assessments as decision support tools for the tradeoffs communities will be faced with making in a resource-constrained future
- Strengthen and support interagency research and monitoring efforts on climate change and impacts on public health and wellbeing
- Invest in programs that can strategically acquire and conserve coastal land, for example, the Coastal and Estuarine Land Conservation Program or the National Estuarine Research Reserve Purchase, Acquisition and Construction program.

Perspectives: NERRS

- Leverage the existence of, and strengthen investments in, federal-state partnership networks like the *National Estuarine Research Reserve System* which can develop, test and deploy solutions to coastal community and ecosystem challenges in a way that strengthens economic, ecological and social resiliency. The reserves are test-beds can be used to rapidly develop, deploy and replicate solutions to adaptation challenges at the local and regional level while collecting baseline information about status and monitoring trends over time. For example, the NERR System piloted a first-in-the-nation assessment (report attached) of marsh resilience comparing the Atlantic and Pacific coasts finding that the tidal marshes in New England were among the most vulnerable to sea level rise and without mitigation and adaptation measures, would lose their ability to provide protection to coastal communities for flooding.
- The Reserves are also at the forefront of innovative and impactful training programs supporting local and regional decision makers charged with developing and implementing adaptation and mitigation strategies in their communities. The trainings are driven by community needs and requests and the science provided is geared towards addressing questions that respond to the community needs. These training programs can be used to fast-track information sharing, technical data and best practice for adaptation solutions. These strategies include deployment of green infrastructure and acquisition of areas sensitive to climate change through the NERRS Purchase, Acquisition and Construction grants.

Question 3. Connecticut residents are already facing the consequences of climate change. How can the United States Northeast ready itself for a warmer world?

Answer.

- Knowledge is power. Universities often provide an extensive source of capacity for relevant knowledge (Climate and Ocean Science, Law, Engineering, Planning, Communications, Geology, Natural Resources) and connections to local stakeholders. Considerable and strategic thought about the role of universities in building a resilient society can be reviewed through *Old Dominion University's Resilience Collaborative Archive,* a summary of which is attached in the appendix.
- The National Estuarine Research Reserves are sources for information about climate change impacts, adaptation strategies and mitigation measures. They

are also a trusted community voice with proven capacity for localized training and community engagement. Fostering collaborations within and among these groups can represent a powerful tool to address changes that can be difficult yet necessary

Issue No. 2: Fostering the Necessary Paradigm Shift to Mitigate Climate Change. This year, two landmark studies were published that document the extent of climate change's impacts on humans and the planet—the Fourth National Climate Assessment and the Global Assessment Report on Biodiversity and Ecosystem Services. Both reiterate in great detail what we have known for decades: climate change is real, humans are causing it, and we must act boldly now. These reports note that our options to mitigate the worst effects of climate change—through domestic policies and international agreements—are insufficient to meet the scale and rate of our changing climate. We need "fundamental, system-wide reorganization across technological, economic, and social factors, including paradigms, goals, and values."

Question 4. How can Congress foster the fundamental, transformational changes needed to save human lives and biodiversity in the face of powerful opposition and inertia?

Answer.

Federal Commitment to Funding Innovations in Partnership with the States

- Congress should provide clear signals about what Federal support for adaptation funding will look like for projects that are critical in states and towns. Many leaders are hoping that Federal funds will reduce the need for local spending. Any programs that are administered by states that provide funds for forward looking adaptation through competitive grants that cost share in the 30–60 percent range would motivate near term action. These programs should push innovative solutions and multiple benefits. These programs should be run through State agencies since there are local political and environmental policies and traditions that must be respected if effective consultation and negotiation is to occur.

Congress should provide leadership and leverage good, existing work

- Make use of the foundations laid over the decade through such things as interagency and White House Office of Science Technology and Policy (OSTP) led efforts on ecosystem services as a framework to use for all Federal science investments.
- Leverage trusted place-based programs like the National Estuarine Research Reserves and their Coastal Training Programs to facilitate town halls, listening sessions, and hearings in the states and regions to seek out leaders, ideas and innovations. The Reserves help to educate and train local officials on developing adaptation strategies and train and educate all members of society in environmental literacy.
- Invite all sectors of society to participate in this effort, with specific outreach and engagement to Tribal nations, indigenous communities, communities of color, the poor, the elderly and youth.
- Engage with the artistic community and storytellers in the creative economy who can help us to build common and positive narratives of living with a changing planet, intentionally, with equity and respect, and within our limits. Challenge this community to help Americans dream big, re-envision and innovate in a future that will look very different than what humanity has known.
- Engage the networks and professions of first responders and healers and find leaders in those communities. Rapid climate change will continue to lead to loss of human life, of the planet's species, habitats, special places and whole ecosystems. These losses will, and already are, causing real grief and anger which have consequences for the mental health of individuals and the public health and wellbeing in communities. This loss needs to be explored, grieved and remembered in a way that promotes healing and hopefully, a better future. At the *Lake Superior Reserve,* for example, we are launching climate change healing circles with the leadership of clinical social workers and Tribal leaders.
- Engage and empower youth in place-based education
  Every year, programs offered at the Lake Superior Reserve and the 28 other Reserves attract more than a half a million students, educators, and visitors. Reserves educate approximately 85,000 students and 3,200 teachers nationwide each year. Since 2011 in Wisconsin and Minnesota, the Lake Superior Reserve's educational programming has reached 52,898 learners.
- Promote and support training for decision makers

Reserve programs help sustain more than 10,000 jobs, provide training to more than 13,400 people. Decision makers from more than 2,500 cities and towns and 570 businesses benefit by Reserve-based science and technical expertise nationwide each year. At the Lake Superior Reserve, we provided training to hundreds of staff from cities, counties, the state, for profit companies and Non-Governmental Organizations each year on topics such as variable Great Lakes water levels, green infrastructure, and nuisance algal blooms. In New Jersey, the *Jacques Cousteau Reserve*-led *Getting to Resilience* community planning tool was cited in the *Northeast Chapter of the National Climate Assessment* as a powerful tool to help communities prepare for extreme storms and flooding.

Issue No. 3: The Need to Invest in Sustainable Infrastructure. As Congress considers a major infrastructure package, we cannot ignore the risks of climate change. Fundamentally new approaches to infrastructure investment are needed, including a focus on clean energy transportation, efficient travel, grid upgrades, and sustainable materials and design. In addition to ensuring that the built environment helps instead of harms humans and the planet, Congress should invest in green infrastructure, including healthy natural spaces. Connecticut's state economy is reliant on the myriad ecosystem services provided by coastal ecosystems, including estuaries, marshes, and open water. I would like to make Connecticut home to the thirtieth National Estuarine Research Reserve (NERR), and I have led efforts to encourage the National Oceanic and Atmospheric Administration to move quickly to approve the proposed Connecticut Reserve. Mitigating climate change's effects on green, blue, grey, and other types of infrastructure is essential for our health and wealth, and deserves Congressional attention.

Question 5. What are some of the most important investments that we can make to ensure our Nation's infrastructure is more resilient or adaptive to the variety of hazards posed by future climate conditions?

Answer.

- Consider the points and recommendations from the September 2019 report from the *Global Commission on Adaptation* (Adapt Now: A Global Call for Leadership on Climate Resilience)—particularly the cases made for the economic return on investments for early warning systems, infrastructure, water and crop resources, and protection for key habitats such as mangroves, wetlands, etc. This report is attached in the appendix.
- As the Kresge report "Rising to the Challenge, Together" details, investments must be made to support proactive and preventative, mitigation measures in communities. This will entail eliminating barriers to such work and increasing opportunities for regional collaborative action.
- Adaptation efforts should also be focused on policy, the role of professional societies and the establishment of standards affecting climate-sensitive structures and activities. An example of this is eliminating the barriers on FEMA funding to reconstruct stormwater infrastructure to the previous state, rather than right-sizing infrastructure proactively to handle heavier precipitation loads.
- Investments that promote green infrastructure or *living shorelines* and those targeting water infrastructure overall will be critical. For example, resources will be critical for mapping and supporting wetland migration corridors, and for facilitating planning processes that focus on citing and relocating infrastructure to safer locations. The public-private partnership, *Living Shorelines Academy* provides a great example of training and resources on this topic. Many of the National Estuarine Research Reserves lead on this as well. For example, Florida's *Guana Tolomato Matanzas Reserve* leads the regional Ecological Engineering of Living Shorelines team focused on solving complex coastal issues through engineering.
- Support the *Digital Coast Act.* This platform has the potential for use by all local planners and can save communities tremendous resources while educating the general public. This user driven resource is supported by a partnership fop eight NGOs and NOAA, so the information is designed to reflect user needs.
- Develop policy that recognizes and respects the biophysical and ecological functioning of watershed systems—regardless of political boundary crossings, and start to expand the definition of what constitutes a 'coastal community.' Congress can rely on and re-authorize the Nation's only land use planning document, the *Coastal Zone Management Act,* as a first step.
- Funding frameworks for infrastructure investments should coordinate between the public and private sector in close collaboration with the philanthropic resources so that complicated gaps can be tackled.

Perspectives: National Estuarine Research Reserves and Integrated Ocean Observing Systems

- A fundamental benefit the NERR system provides is the built-in capacity for monitoring key environmental parameters that can be used in many capacities in adaptation and mitigation strategies. The Reserve System maintains more than 280 water quality and weather monitoring stations. Every 15 minutes, these platforms collect data to manage hazardous spills, shellfish industry operations, and emergency response to storm surge and flooding. That's 42 million data points each year tracking the changing health of our critical coastal systems. The measurements taken and data products provided span a national scope but detail impacts at local scales—which is necessary for discriminating the sensitivities of impacts. This network capacity should be expanded and could easily be done given the tools and technology already in place.
- Similarly, increased investments towards the *US Integrated Ocean Observing System* and regional associations are needed to provide increased capacity of warnings and long term monitoring of environmental indicators.

Question 6. How does the preservation of coastal habitat—such as those in the NERR system—help mitigate the effects of climate change on infrastructure?

Answer.

- It is well documented that coastal habitats provide critical buffering capacity from the landward effects of storms and the expected impacts of things sea level rise. The continued efforts to both preserve and restore these habitats are essential components in any strategy to mitigate effects of climate change.
- The wetlands in the NERR System make their coastal areas more resilient in the face of increased and intensifying storms and flooding. Nationally, wetlands, like those Reserves protect, provide $26.25 billion in storm protection each year. Salt marshes can reduce a community's storm damage by 20 percent annually. Marshes reduce risk of flood exposure by 50 percent for those living within two thirds of a mile—they also reduce property loss in upstream communities. Reserves overall protect more than 1.3 million acres of coastal and estuarine lands around the country. States, communities, and people depend on these estuaries to protect them from flooding, keep water clean, sustain and create jobs, support fish and wildlife, and offer outdoor recreation. By increasing Federal funds in the NERRS Purchase, Acquisition and Construction grants, communities can be strategic in their purchase and conservation of high quality coastal habitat.
- Coastal wetlands are nature's most effective carbon trapping machines—inch for inch they capture more carbon than any other habitat on earth. They also protect water quality, stabilize shorelines, reduce storm surge, and provide habitat for fisheries. Unfortunately, since 2005 alone, the U.S. has lost 80,000 acres of wetlands, and the cost of restoration is often beyond community reach. Restoring degraded wetlands has the potential to be an effective climate mitigation strategy with rapid rewards. Voluntary blue carbon markets can help pay for wetland restoration and conservation. Communities, businesses, and individuals can sell carbon offsets and invest the proceeds in projects that capture carbon and provide other important ecological and economic benefits. Through the National Estuarine Research Reserve (NERRS) network, knowledge gained through the Bringing Wetlands to Market project in New England is catalyzing blue carbon initiatives around the country.

RESPONSE TO WRITTEN QUESTIONS SUBMITTED BY HON. EDWARD MARKEY TO ERIKA WASHBURN, PH.D.

Question 1. Low income neighborhoods and communities of color disproportionately bear the brunt of climate impacts. How can Congress support and incorporate social science to ensure that adaptation planning is equitable and protects frontline communities?

Answer. Congress needs to provide an equitable and collaborative adaptation planning process. This process includes:

- Ensure Federal funding programs require engagement and demonstrated support beyond state and municipal partners (*e.g.,* neighborhood-scale/community-based organizations) to advance equitable (and often more integrated, systemic) adaptation planning initiatives.
- Provide funding opportunities for organizations advancing holistic regional adaptation planning processes in communities of color around the Nation (*e.g.,*

The Climigration Network) and increase Federal support for collaborative planning efforts that are supported by staff with professional facilitation experience who can equitably balance the needs of competing interests. Cognizant of the capacity requirements and additional burden grant writing often places on already disadvantaged communities, these Federal funding opportunities should be simplified to the minimum necessary, be coordinated as much as possible with other funding streams or be funneled through and coordinated with other funding opportunities through streamlined regional grant-making organizations, and involve technical assistance for those writing funding proposals and administering Federal funds.

- Restructure Army Corps of Engineers efforts to generate, evaluate and implement coastal and inland risk management strategies (*e.g.,* shoreline protection, surge gates) to provide real and meaningful stakeholder engagement and dialogue with all stakeholder groups, but especially with low income neighborhoods, communities of color and Indigenous communities. Create provisions, including adequate staff, funding, technical support, and training opportunities and support strategic partnerships with organizations that have relevant outreach and engagement expertise (*e.g.,* NERRs, *Regional Integrated Sciences and Assessments Program,* the *National Sea Grant College Program,* U.S. Department of Agriculture climate hubs, and other existing professional networks such as *Urban Sustainability Directors Network,, American Society of Adaptation Professionals,* etc.) to ensure two-way dialogue and a complete community understanding of the short-term and long-term implications of implemented strategies including visual, access, residual risk and cost factors.

Congress needs to ensure that adaptation planning is equitable and protects frontline communities, which are already experiencing the impacts of climate change and include such places as coastal and low-lying river and tributary communities, communities subject to intense heat waves and droughts, communities with persistent water scarcity, and communities on the leading edge of new vector borne diseases.

Equitable adaptation planning must start with recognition that there is often disparity in the vulnerable of different sectors of society to impacts from climate change and coastal hazards. Some of the most vulnerable groups include low income neighborhoods, the elderly, the very young, and the disabled, with long legacies of racial disparities and disadvantages aggravating these demographic factors.

Congress could assist with ensuring that frontline communities are protected by:

1. Ensuring that Federal grant program and other federally supported efforts aimed at advancing adaptation planning for climate change explicitly integrate consideration for disparity in vulnerability to impacts from climate change for different socioeconomic groups as part of all adaptation planning projects and programs. Further, increase support for projects/programs that aim to directly study and integrate social science considerations for adaptation planning.
2. Continue supporting programs that seriously consider long-standing, systemic and persistent environmental justice issues.
3. In recognition of the fact that there can be a concentration of low income neighborhoods in urban settings and that often low income earners are renters of property in urban settings, ensure that realtors and landlords are educated about potential impacts from climate change. Work with the real estate sector and landlords to educate renters about potential climate change threats. For example, heat health impacts can be huge in urban settings and heat-related threats will be a main impact of climate change. Ensuring that cooling centers, tree planting programs etc. are supported in these urban settings could be very important and help to save lives.
4. Support programs that enable homeowners and owners of rental properties to retrofit their homes to address structural vulnerabilities to storms and other risks that could be exacerbated by climate change. Incentives should be staggered, *i.e.,* larger for those with low and lower incomes than for wealthier home owners, and they should be accompanied with simplified application procedures and technical assistance so as not to perpetuate the commonly observed pattern whereby wealthier, higher-capacity property owners have greater capacity to apply for and ultimately receive financial assistance for retrofits.

Perspectives: National Estuarine Research Reserves Related Studies/Projects

- The Research Reserves are increasingly tackling this challenge. For example, a capacity building study led by *Waquoit Bay Reserve* in Massachusetts focused on working towards coastal resilience for underserved/hard to reach community members on Cape Cod. This Reserve also recently developed an innovative program meeting the needs of vulnerable audiences focused on the deaf and hearing impaired. More information about this NERRS Science Collaborative funded Watershed Action for Deaf Education (WADE) is attached in the appendix. While this project did not explicitly address climate change it shows a successful process used to engage and serve an underserved audience. Additional information is available on page 11 of this *NOAA Education Accomplishments Report.*

Other relevant work by active adaptation players

- The *Movement Strategy Center* has developed a guide for adaptation/resilience planning that is sensitive to community-concerns and illustrates a fully community-engaged adaptation process. We attach it and consider it a model for others to follow.
- The *National Association for the Advancement of Colored People, Asian Pacific Environmental Network, Urban Sustainability Directors Network* and *US Water Alliance* have also developed a series of relevant guides that illustrate how equity-centered resilience building, preparedness planning, rebuilding after disaster and so on should be done to address historic patterns of injustice and inequity. Many examples from these groups are attached in the appendix.
- Look to great examples in the Nation such as the work being done by the *Community Resilience Initiative in Oakland,* California, which has successfully demonstrated a process to improve equity actions by state and local agencies. Likewise, explore the Rockefeller Foundation's *100 Resilient Cities* initiative for more examples.
- Engage a full range of social scientists and associated human dimensions data and information into the debates, structures and proposals for a national adaptation policy and associated funding mechanisms. Do this leveraging agencies, Federal agencies, programs (some with regional arms) such as all *US Global Change Research Program* (USGCRP) agencies, especially the Department of Commerce/NOAA funding programs (*e.g., Regional Integrates Science And Assessments Program, Sectoral Applications Research Program, National Sea Grant College Program,* etc.), USDA (*e.g.,* Cooperative Extension, Forest Service), the National Science Foundation, Environmental Protection Agency, and Department of Interior (with the U.S. Geological Survey, Fish and Wildlife Service, National Park Service, Bureau of Indian Affairs, etc.), National Institutes of Health, Centers for Disease Control and Prevention, Housing and Urban Development, the Census, Bureau of Labor, and place-based interdisciplinary programs like the NERRS and others.
- Professional societies such as the *American Society of Adaptation Professionals,* the *American Planning Association, American Society of Civil Engineers, American Psychological Association, American Psychiatric Association, American Medical Association,* and other professional societies representing relevant areas of research and academic expertise, such as the *American Association of Geographers,* the *American Anthropological Association, Society for Applied Anthropology, American Sociological Association* and many others can all support this.

Question 2. What Federal investments, programs, or partnerships are needed to meet our Nation's social science needs for understanding the human dimensions of the climate crisis?

Answer.

Federal investments, programs and partnerships that engage and leverage social science towards understanding the human dimensions of the climate crisis and providing guidance on best practice for adaptation, will be critical in the following: ensuring climate justice, tracking progress towards successful adaptation, facilitating cross-jurisdictional coordination, and supporting the relocation of communities/domestic climate refugees. Applied social science will be critical in tracking and sharing lessons learned in adaptation across our Nation at all scales, and this will further require enhanced investment in the social science workforce.

Climate justice as a cross-cutting guiding principle: Given that low income communities and communities of color have contributed the least to the climate change problem, are expected to suffer the most absent concerted effort, and have—left to their own devices—the least resources to prepare for and protect themselves from

the impacts of climate change, climate justice should be a cross-cutting concern or principle in all federally-funded adaptation efforts.

A. Establish a Climate Justice Advisory Board. Create an environmental justice advisory committee at the highest level to provide input into the planning and implementation of adaptation initiatives. Consider the model of the *NYS Climate Leadership and Community Protection Act* which creates a Climate Justice Working Group responsible for setting the criteria for identifying disadvantaged communities and advising on the implementation of the Act.

B. Add climate justice requirements to Federal funding. Develop language for and require attention to climate justice in all Federal funding programs.

Adaptation success/progress: Set up a standing cross-agency working group or task force (including at least all USGCRP agencies, but also relevant others, see Question 1 above) to scan the horizon on how to measure and track national-level indicators and metrics of adaptation progress and success. Considerable work was done beginning with *3rd National Climate Assessment,* and has continued somewhat but mostly outside of Federal agencies within universities and programs such as the NERRS with development of adaptation indicators and metrics.

A. Continue and strengthen work on adaptation indicators and progress. Building on the work done to date within and outside Federal agencies, the USGCRP should develop a set of scientifically credible and decision-relevant, actionable adaptation progress indicators. These indicators are to be considered in the quadrennial National Climate Assessments, be included in the Federal government's *Resilience Toolkit,* and help inform and guide future climate preparedness investments. These indicators should pay particular attention to what extent progress is being made addressing climate justice and in so doing, reducing social vulnerability of these historically most disadvantaged groups. Indicators should be crafted that can track the success of adaptation initiatives with this in mind.

B. Invest in the development and deployment of regional networks and tools to collect baseline information about frontline coastal communities concerning social, cultural, economic and health data. This would result in real-time tackling of community social vulnerability. Tracked over time and at a granular enough scale, this data would describe a community's resiliency, health and wellbeing and would be useful to decision makers weighing investments, policies and adaptation strategies to deploy. Limited examples that could be built upon include *NOAA's Digital Coast social vulnerability* index, and *New York Sea Grant's Coastal Resilience Index,* which engaged social science to develop a post-flood recovery visioning initiative to identify gaps and barriers to adaptation, which included a flood inundation mapping package and online mapping tool.

Cross-jurisdictional coordination: Adaptation will require much greater communication and collaboration across jurisdictions and scales than is currently done. Funds should be made available through such things as the Department of Commerce's *Economic Development Administration,* in support of these cross-jurisdictional communication and collaboration mechanisms. One critical way this could be institutionalized is to expand funding for Sustained Assessment specialists.

A. Cross-jurisdictional communication. Host regular regional facilitated dialogues with participants across scales (*e.g.,* neighborhood, municipal, regional, state, federal) and within scales (*e.g.,* regional convening of state and Federal program staff to share challenges, needs, opportunities) to understand the real and perceived barriers to climate adaptation with an emphasis on meeting targets for disadvantaged communities. NERRS would be logical hosts for conversations of this nature.

B. Cross-jurisdictional partnerships. Supporting new and innovative partnerships such as partnerships between state and local programs working to better understand human dimensions of climate change and support communities with adaptation planning efforts, with local groups that serve the needs of the most vulnerable in the community. (E.g. Partnerships with Service Centers, Faith Communities, Business Community, Realtors and Chambers of Commerce)

Getting out of harm's way: getting out of harms' way involves, avoiding getting into it and—once in it—helping people relocate out of it. This speaks to various Federal efforts, policies and programs:

A. Review Federal insurance programs. This would ensure they reflect the actual risk; moving toward the place where insurance rates and premiums reflect current and future risks.

B. Require forward-looking climate science in infrastructure planning. Require that all Federal infrastructure funds consider scenarios of future risk over 30-, 50- and 100-year time frames and that infrastructure is planned and built to be adaptive, given uncertainties about the exact extent of future climate change; the process used by Federal programs and agencies should be consistent with procedures practiced at the General Services Administration.

C. Discontinue investment and development in at-risk location. Review any other Federal investment and incentive programs that encourage people to move into high-risk areas and phase out those programs or ensure that they redirect development and people's movement toward safer locations.

D. Improve buyout programs. Invest heavily in the restructuring of Federal buyout programs, support the development and growth of state buyout programs and improve the overall buyout process—which is not meeting national needs at many levels. Adjust administration and create flexible funding structures to dramatically decrease wait times for real estate transfers, support high quality temporary housing in safe locations and create robust support services that make this transition rapid and comfortable. Offer meaningful financial support and other assistance to renters interested in relocating. Offer financial and other incentives to communities safe from flooding to encourage reception of homeowners in transition. Provide necessary outreach and engagement with homeowners in transition to ensure they do not repurchase a new property in an area of high flood risk.

Continue and expand place-based research and facilitate lesson sharing nationally

- Continue to support investments in federally funded place-based, solutions-oriented, stakeholder-engaged programs such as the NOAA funded National Estuarine Research Reserves, the NERRS Science Collaborative competitive grant program, the National Sea Grant College Program and Coastal Zone Management Program, EPA funded National Estuaries Program, and USDA funded Cooperative Extension. One NOAA funded program attached to the NERRS, the Science Collaborative, specifically funds research that is aimed at addressing community needs and use a collaborative model that increasingly incorporates social science approaches in engaging different audiences. Using this collaborative research approach has been shown to be very successful and benefits communities. It is important, however, to extract generalizable lessons to foster accelerated learning and spread effective solutions to other locations. The quadrennial National Climate Assessments and the sustained assessment process should be used to extract generalizable lessons so that adaptation practice and solutions are more readily implemented elsewhere.

Perspectives: National Estuarine Research Reserves

- The reserves support research on partnering with faith communities to address climate change. Waquoit Bay Reserve in Massachusetts supported an effort called 'NERRS as common grounds: towards a holistic science approach to research, education, and outreach with religious communities to enhance climate and environmental literacy' the findings of which are attached in the appendix.

Workforce development: In recognition of the needs to be further training of the next generation of adaptation professionals—in whatever fields they find themselves—it is essential to invest in education, trainings and accelerated professional development. A number of tracks must be pursued:

A. Develop professional standards. Given that adaptation is a high-risk endeavor with millions of people's lives and well-being and trillions of dollars at risk in coastal areas alone, adaptation, preparedness, and resilience-building should be conducted in appropriate ethical, technically skilled and economically sound manner, informed by the best climate and social science. Currently there are no professional standards, but various professional development efforts underway. The Federal government should consider initiating a process whereby relevant standard-setting institutions are brought together to consider ongoing professional development and set minimum standards in professional skills and conduct.

B. Build the pipeline. While many think of adaptation as a technical matter, the range of skills for effective adaptation is much broader. Training in the relevant social and applied sciences and topics (*e.g.,* planning and policy-making

processes, communication, vulnerability assessments, economic assessments, finance, law, physical and mental health) is required across the board. There is also a need to increase awareness of social science fields as important career options required to meet the climate change crisis. Partnerships with colleges and universities as well as professional societies are essential, but efforts must be made to reach deeper into the K–16 school system to help educate young people about the role of social science in helping to address societal issues like climate change that will be with us for a long time. This is a very long term view but recognizes the need for further training of career professionals working on climate change issues. This topic is further expanded in 'Rising to the Challenge, Together' attached in the appendix.

APPENDICES AND LINKS TO RESOURCES

Climate Resilience

- *Adapt Now: A global Call for Leadership on Climate Resilience.* Global Commission on Adaptation
- *Rising to the Challenge, Together: A Review and Critical Assessment of the State of the U.S. Climate Adaptation Field.* Moser *et al.,* Kresge Foundation.
- *Change Adaptation: An Action Toolkit.* National Association of Climate Resilience Planners.
- *Institutionalizing Resilience in U.S. Universities: Prospects, Opportunities, and Models.* Foster et al.
- *Mapping Now: A Blueprint for Thriving in the Face of Climate Disasters.* Apen.
- *Pathways to Resilience: Transforming Cities in a Changing Climate: Kresge Foundation, Movement Strategy Center, Movement Generation, The Praxis Project, Reimagine!,* RP&E
- *Community-driven Climate Resilience Planning: A Framework.* National Association of Climate Resilience Planners.
- *Our Communities, Our Power: Advancing Resistance and Resilience in Climate*
- *Bounce Forward: Urban Resilience in the Era of Climate Change.* Kresge Foundation & Island Press.

Social Equity & Justice

- *Watershed Stewardship in Action: Deaf Students on the Estuary.* NERRS Science Collaborative.
- *Working Towards Coastal Resilience for Underserved/Hard to Reach Community Members on Cape Cod.* Waquoit Bay National Estuarine Research Reserve.

An Equitable Water Future: A National Briefing Paper. US Water Alliance.

- *A Guide to Equitable, Community-Driven, Climate Preparedness Planning.* Urban Sustainability Directors Network.
- *Climate Change Through an Intersectional Lens: Gendered Vulnerability and Resilience in Indigenous Communities in the United States.* Vinyeta *et al.,* USDA
- *Unleashing the Power of the People: Lessons on Public Engagement for Environmental and Climate Justice.* National Association of Climate Resilience Planners.
- *Equity in Building Resilience in Adaptation Planning.* National Association for the Advancement of Colored People.
- *In the Eye of the Storm: A People's Guide to Transforming Crisis & Advancing Equity in the Disaster Continuum.* National Association of Climate Resilience Planners.

Wetlands & Climate Resilience

- *NERRS Blue Carbon: Putting Wetland Restoration & Conservation in Reach.* NERRS
- *Rising to the Challenge: Will Tidal Marshes Survive Rising Seas?* Wasson, Raposa, *et al.,* NERRS
- *National Estuarine Research Reserves (NERRs) as common grounds: towards a holistic science approach to research, education, and outreach with religious communities to enhance climate and environmental literacy at Waquoit Bay, Cape Cod, Massachusetts, USA.* Greber et al.

Web Resources for Senator Blumenthal's Office

Connecticut institute for Resilience & Climate Adaptation. An excellent resource for a range climate-related science, policy, and initiatives, including:

- Green Infrastructure:
  - MetroCOG—Designing Resilience: Living Shorelines for Bridgeport
  - Milford—Developing and Implementing a Restoration and Management Plan to Combat Threats and Challenges to Coastal Dune Resiliency in Urban Landscapes
- Critical Infrastructure:
  - Municipal Resilience Planning Assistance for Sea Level Rise, Coastal Flooding, Wastewater Treatment Infrastructure, & Policy
- Inland Flooding:
  - RiverCOG Lower Connecticut River Valley Regional Council of Governments—Regional Long Term Recovery-Land Use Resiliency Plan
- Coastal Flooding:
  - Jarvis Creek Sea Level & Flooding Variability
- Policy/Planning:
  - Connecticut Physical Climate Science Assessment Report
  - Developing Location-Based Communication and Public Engagement Strategies to Build Resilient Coastal Communities
- Sea-Level Rise:
  - Advancing High Resolution Coastal Forecasting and Living Shorelines Approaches in the Northeast

Connecticut Sea Grant Resilient Communities

- Beaches & Dunes:
  - Hazard Guide for Property Owners
- Resilient Communities
  - Climate Adaptation Academy

Sea Level Rise Effects on Roads & Marshes: University of Connecticut Center for Land use Education & Research

CT Dept of Energy & Environmental Protection (DEEP):

- Public Act 12–101, An Act Concerning the Coastal Management Act and Shoreline Flood and Erosion Control Structures
- Sea Level Rise Scenarios
- CT Climate Change

Office of the Governor:

Executive Order on Climate Change Mitigation

○