WHAT'S THE FORECAST: A LOOK AT THE FUTURE OF WEATHER RESEARCH

HEARING

BEFORE THE

SUBCOMMITTEE ON ENVIRONMENT

OF THE

COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY

OF THE

HOUSE OF REPRESENTATIVES

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C O N T E N T S

June 14, 2022

WHAT'S THE FORECAST: A LOOK AT THE FUTURE OF WEATHER RESEARCH

TUESDAY, JUNE 14, 2022

HOUSE OF REPRESENTATIVES,
SUBCOMMITTEE ON ENVIRONMENT,
COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY,
Washington, D.C.

The Subcommittee met, pursuant to notice, at 10 a.m., in room 3218 of the Rayburn House Office Building, Hon. Mikie Sherrill [Chairwoman of the Subcommittee] presiding.

COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY
SUBCOMMITTEE ON ENVIRONMENT
U.S. HOUSE OF REPRESENTATIVES
HEARING CHARTER

What's the Forecast: A Look at the Future of Weather Research

Tuesday, June 14, 2022
10:00 AM EDT
2318 Rayburn House Office Building and Online via Zoom

Purpose

This hearing will provide an opportunity to discuss the highest priority investments needed for weather research and development over the next decade, as described in the National Oceanic and Atmospheric Administration (NOAA) Science Advisory Board (SAB)'s "Priorities for Weather Research" report. This discussion will include perspectives from the U.S. Weather Enterprise, comprised of public, private, and academic partners. This hearing will also examine how investments in weather research and development can protect critical infrastructure, life, property, and enhance equity in the provision of weather services, while supporting the national economy.

Witnesses

- **Dr. Scott Glenn,** Board of Governors Professor, Center for Ocean Observing Leadership of the Department of Marine and Coastal Sciences, Rutgers University
- **Dr. Bradley Colman,** President-Elect of the American Meteorological Society; Director of Weather-Strategy, Bayer & The Climate Corporation
- **Dr. Fred Carr,** Professor Emeritus, School of Meteorology, University of Oklahoma
- **Dr. Kevin R. Petty,** VP, Weather and Earth Intelligence, Spire Global, Inc.

Overarching Questions

- How can investments in weather research and development support the economy, protect life and property, and protect critical infrastructure investments?
- What federal investments in weather research and forecasting are most needed to improve U.S. weather forecasting?
- How can the federal government leverage the U.S. Weather Enterprise to accelerate implementation of weather research priorities over the next decade?
- What are the workforce needs to meet the weather priorities for the next decade?
- How can the Weather Enterprise ensure that weather forecast products and services are disseminated in an equitable manner?
- What types of weather infrastructure (dissemination networks, Earth observing networks, high-performance computing, etc.) is needed to meet the growing needs of a nation experiencing increasingly frequent and intense extreme weather events?

Background

The Weather Research and Forecasting Innovation Act of 2017, [1] and its 2019 reauthorization,[2] directed NOAA to improve its weather forecasting capabilities by advancing observations, modeling, and computing. In additional to overall improvements in forecasting capabilities, the implementation of the Weather Act has resulted in the development of NOAA's Earth Prediction Innovation Center (EPIC), and the codification of the Environmental Information Services Working Group (EISWG) and of NOAA's Impact-Based Decision Support Services (IDSS).

Since 2017, the U.S. has experienced weather and climate disasters that exceed $740 billion, with 2021 in second place for the most billion-dollar disasters in a calendar year, and the deadliest in terms of disaster-related fatalities in the contiguous U.S. since 2011.[3] This evidence shows a clear need to continue improving weather forecasting capabilities to protect life and property.

Priorities for Weather Research Report

In the Fiscal Year 2021 Omnibus Consolidated Appropriations Act,[4] Congress charged the NOAA SAB to publish a report to inform the necessary federal investments needed in weather research and forecasting over the next decade. The NOAA SAB published the Priorities for Weather Research (PWR) report which took into consideration the input of over 150 subject matter experts across the Weather Enterprise in development of its recommendations. The report recommends accelerated and increased investments in priority areas that are both balanced and constructive to the weather information value chain.[5]

The PWR report highlights five narrative themes to convey the importance of the scientific and technical recommendations in the report: Mission Critical Mile; Highly Reliable, Fully Accessible Weather Information; Improve Predictions of Water Cycle Extremes and Their Cascading Impacts; High-Impact Weather; and Global Leadership in Weather Prediction as a Pathway to Higher Quality Products and Services. These five themes underscore the importance of the recommendations identified under four core areas—Research and Development; Infrastructure; Actions and Impacts; NOAA Prioritization and Investment—of the PWR report.[6,7] The cornerstone of the narrative themes identified by the PWR report is the development and implementation of a fully-coupled Earth System Model.

Earth System Model

The Earth System Model (ESM) is a mathematical model of the physical, chemical and biological processes that affect weather and climate. The relevant systems include the atmosphere, oceans, land surface, cryosphere, biosphere and hydrologic and biogeochemical cycles, and the interactions (coupling) among them. Collectively improving the observations,

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[1] P.L. 115-25
[2] P.L. 115-423
[3] https://www.climate.gov/news-features/blogs/beyond-data/2021-us-billion-dollar-weather-and-climate-disasters-historical
[4] P.L. 116-260
[5] NOAA Science Advisory Board, 2021: A Report on Priorities for Weather Research. NOAA Science Advisory Board Report, 119 pp. https://sab.noaa.gov/wp-content/uploads/2021/12/PWR-Report_Final_12-9-21.pdf
[6] Ibid
[7] Ibid

understanding, and data assimilation of the connected systems and interactions will advance the scope of knowledge of the Weather Enterprise, and the lay public. NOAA currently employs an operational weather forecast model known as the Global Forecast System (GFS).[8] The PWR report notes that in the current forecasting system, observation gaps exist in the planetary boundary layer observations, as well as high-impact weather and water cycle extreme observations. The comprehensive scale of the ESM would fill the gaps that are currently present.

Federal investments support the U.S. Weather Enterprise

The U.S. Weather Enterprise is comprised of the public, private, and academic sectors that work collaboratively to provide timely and accurate weather products and services. The Science Committee held a hearing on the U.S. Weather Enterprise in May 2019.[9] The private sector has seen significant advancement in their research and forecasting capabilities. The foundation of the Weather Enterprise continues to be the public sector, primarily through federal investments for NOAA's National Weather Service (NWS); the civilian agency responsible for issuing terrestrial and space weather watches, warnings, and advisories. The NWS provides the critical underlying data, resources, and information that is essential to the Weather Enterprise.

While the recommendations in the PWR report are focused on needed federal investments, the outcome of these investments will support the broader Weather Enterprise's efforts to improve U.S. weather forecasting. The development and integration of a fully coupled ESM will benefit from federal investments in high-performance computing outlined in the report; investments that academia and the private sector cannot make on their own.

NOAA uses numerical weather prediction (NWP) to develop forecasts by utilizing data from space-and ground-based observation platforms that feed into high-performance computer models that make predictions about weather conditions.[10] Additionally, NOAA's ongoing efforts through EPIC, has transitioned the code for the Unified Forecasting System (UFS) to Github, where it can be publicly accessed. The UFS is EPIC's solution to a community-based, coupled, comprehensive Earth modeling system used for various NWP applications. The ESM recommended in the PWR report will require regular, publicly accessible, updates to NOAA's weather model code to ensure continued collaboration with academia and the private sector, who often utilize more recently developed coding languages.

Commercial weather providers have developed add-on weather products and services, and in some cases, augmented federal weather data. However, the necessity of federally procured weather data remains indisputable. Most foundational weather observations that serve as the backbone of all weather forecasts are dependent upon federal investments that support both data collection and assimilation. Federal investments in the provision of weather data, development of forecast models, and accessibility of high-performance computing resources allows the private and academic sectors the ability to drive innovation in the development and dissemination of cutting-edge weather products and services to the public.

An important aspect of the Weather Enterprise is the weather information value chain, a concept in which hydrological-meteorological systems are observed and modeled resulting in forecasts and warnings. The information is then disseminated through channels and potentially altered by

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[8] https://www.ncei.noaa.gov/products/weather-climate-models/global-forecast
[9] https://docs.house.gov/Committee/Calendar/ByEvent.aspx?EventID=109467
[10] https://www.weather.gov/rah/virtualtourforecast

secondary information providers such as private weather services, media channels, and mobile platforms to be communicated.[11] There are still significant investments needed in information dissemination to reduce the impacts of extreme weather, water, and climate events. The PWR report recommends investing in artificial intelligence, cloud technologies, and assimilating social and behavioral data to anticipate user needs.[12] Investing in information dissemination can increase the present value of capabilities that already exist.

NOAA's short term forecasting capabilities to disseminate weather forecasts days to weeks in advance is robust. These forecasts are utilized daily for decision making by the public as well as public and private industry professionals such as fire responders and grid operators. However, the need to improve forecasting on the subseasonal to seasonal (S2S) timescale (two weeks to two years) remains a key priority for NOAA and many of the PWR report recommendations would support these efforts. Improving S2S forecasts has become increasingly important to determine seasonal drought and precipitation forecasts, and temperature outlooks. Improved forecast accuracy at greater timescales provides decision-makers additional time to prepare and communicate the weather threats they are facing to the public.[13] Supporting assimilation of existing observations and data in conjunction with developing novel assimilation methods of boundary layer observations and data is essential to improving S2S forecasts.[14]

Behavioral and Social Sciences

The PWR report detailed the importance of the "Mission Critical Mile," which is defined as the combination of understanding audiences (the "first mile") and the delivery of weather information to those audiences (the "last mile").[15] The behavioral and social sciences must be fully engaged to maximize the return on meteorological research and weather prediction. Investments in leadership to build awareness, and capacity throughout the Weather Enterprise, especially to identify critical knowledge gaps within weather forecasting and communication, will support better engagement with end-users of weather information. Increasing the integration of behavioral and social sciences into the development of weather services is a key component in addressing issues of weather information inequity. Community-centered communication approaches that are accessible and tailored, including issuing warnings in alternative languages in non-English-speaking communities are an example of such approaches that close the gap in information inequities.[16]

[11] https://www.ametsoc.org/ams/assets/File/policy/WWC_Value_Chain_Economic_Benefits.pdf
[12] https://sab.noaa.gov/wp-content/uploads/2021/12/PWR-Report_Final_12-9-21.pdf
[13] https://www.nerc.com/pa/RAPA/ra/Reliability Assessments DL/NERC_SRA_2022.pdf
[14] https://sab.noaa.gov/wp-content/uploads/2021/12/PWR-Report_Final_12-9-21.pdf
[15] https://sab.noaa.gov/wp-content/uploads/2021/12/PWR-Report_Final_12-9-21.pdf
[16] https://sab.noaa.gov/wp-content/uploads/2021/12/PWR-Report_Final_12-9-21.pdf

Additional Resources

- World Meteorological Association's 2021 Future of Weather and Climate Forecasting[17]
- National Academies 2003 Fair Weather: Effective Partnerships in Weather and Climate Services[18]
- National Academies 2018 Integrating Social and Behavioral Sciences Within the Weather Enterprise[19]
- NOAA Hurricane Forecast Improvement Program (HFIP) R&D Activities Summary: Recent Results and Operational Implementation[20]

Relevant Recent Science Committee Hearings

- May 16, 2019 – The Future of Forecasting: Building a Stronger U.S. Weather Enterprise[21]
- July 22, 2019 – Weathering the Storm: Improving Hurricane Resiliency through Research[22]
- September 26, 2019 – Understanding, Forecasting, and Communicating Extreme Weather in a Changing Climate[23]
- November 20, 2019 – A Task of EPIC Proportions: Reclaiming U.S. Leadership in Weather Modeling and Prediction[24]
- September 30, 2020 – Coping with Compound Crises: Extreme Weather, Social Injustice, and a Global Pandemic[25]
- October 14, 2021 – The Future of Forecasting: Building a Weather-Ready Nation on All Fronts[26]

[17] https://library.wmo.int/doc_num.php?explnum_id=10611
[18] https://nap.nationalacademies.org/catalog/10610/fair-weather-effective-partnership-in-weather-and-climate-services
[19] https://nap.nationalacademies.org/catalog/24865/integrating-social-and-behavioral-sciences-within-the-weather-enterprise
[20] https://hfip.org/sites/default/files/documents/hfip-annual-report-2020-final_0.pdf
[21] https://docs.house.gov/Committee/Calendar/ByEvent.aspx?EventID=109467
[22] https://docs.house.gov/Committee/Calendar/ByEvent.aspx?EventID=109575
[23] https://docs.house.gov/Committee/Calendar/ByEvent.aspx?EventID=109982
[24] https://docs.house.gov/Committee/Calendar/ByEvent.aspx?EventID=110243
[25] https://docs.house.gov/Committee/Calendar/ByEvent.aspx?EventID=111061
[26] https://docs.house.gov/Committee/Calendar/ByEvent.aspx?EventID=114122

Chairwoman SHERRILL [continuing]. About the conduct of this hearing. First, Members and staff who are attending in person may choose to be masked, but it is not a requirement. However, any individual with symptoms, a positive test, or exposure to someone with COVID–19 should wear a mask while present.

Members who are attending virtually should keep their video feed on as long as they are present in the hearing. Members are responsible for their own microphones. Please also keep your microphones muted unless you are speaking.

Finally, if Members have documents they wish to submit for the record, please email them to the Committee Clerk, whose email address was circulated prior to the hearing.

Good morning. Welcome to today's hearing on the future of weather research. Before we begin, I would like to take a moment to extend my sincere condolences to our colleague, Representative Sean Casten, whose daughter passed away yesterday. I am deeply sorry for his loss, and my thoughts are with him and his family during this difficult time.

I'd now like to welcome all of our esteemed witnesses to today's hearing in person after two years of virtual and hybrid testimony.

Weather forecasting plays an integral role in society and a crucial role in protecting lives during extreme weather events. You may not realize it, but each and every American benefits from the Federal investment made to support the National Weather Service (NWS) every day. Whether you are using a weather app on your phone or watching your local meteorologist on the evening news, these products and services depend on Federal weather data. Weather forecasting is consistently relied on to guide planning across the U.S., whether it's deciding whether to take an umbrella on a work commute, planning an outdoor gathering with friends and family, or determining a seasonal crop plan.

My district has firsthand experience in the devastation that can be caused from extreme weather. The effects of Hurricane Sandy are still being felt by my constituents a decade later. The Hudson Tunnel remains compromised, and a project to rehabilitate the tunnel began only as recently as last year. While the Weather Service has significantly improved the accuracy of the hurricane track forecasts since Hurricane Sandy, there remains a need to improve intensity forecasts as well.

I'm looking forward to hearing from Dr. Scott Glenn of Rutgers University on how funding from the Sandy Supplemental was critical to his research to better predict and understand hurricanes and why robust and consistent Federal funding is necessary to support the transition from weather research to operations.

When considering the future of forecasting, it is crucial that long-term forecasting is also part of the conversation. The Northeast Regional Climate Center reports that over the past 20 years, New Jersey has had an increase in extreme precipitation. The report further predicts that precipitation intensity will continue to increase in my district by up to 50 percent over the next 80 years from what was observed at the end of the 20th century as a result of climate change. In a region that has seen the impacts of localized flooding events cause hard hits to homes and businesses, this report is alarming.

Just last September, we lost 27 lives across New Jersey in the wake of Tropical Storm Ida. The sudden intensity and precise location of rainfall and flooding was difficult to predict. Emergency responders rescued people from roadways and homes where they did not expect flooding to impact them. I heard from a mother in my district who, along with her young children, had to be rescued from her home at night during Hurricane Ida. She said that she had been told at 5 p.m. that the storm would pass to the west. Empowering residents with accurate long-term and short-term precipitation models will give them the information they need when planning a move or a new business location or preparing for an accurate weather event like—acute weather event like Ida.

Improving our understanding of precipitation trends and hurricane intensity is not just important for my constituents but for all Americans. The accuracy of short-term weather forecasts in the range of a few days to two weeks has improved significantly in recent decades. However, there remain gaps in our ability to provide sub-seasonal to seasonal forecasts. Improved longer-term forecasts that are on the order of weeks to months would support the resiliency of critical infrastructure sectors like transportation, utility, and energy sectors that we rely on every day.

To better understand what is needed to improve weather forecasting, Congress requested a report to identify necessary weather research investments. The Priorities for Weather Research, or PWR, pronounced "power," report is a compilation of expert recommendations from across the U.S. Weather Enterprise, made up of public, private, and academic partners. This report highlights the investments needed over the next decade in weather research, observations, modeling, forecasting, and dissemination. It takes into consideration how Federal investment in weather research supports the private and academic sectors of the weather enterprise. We are fortunate that our witness panel today includes not only the co-authors of this report but perspectives from across the Weather Enterprise.

In the midst of another Atlantic Hurricane season predicted to have above-normal activity, accurate forecasts coupled with timely dissemination will be necessary to ensure the safety and protect the livelihoods of Americans along the Gulf and East Coasts.

I look forward to hearing more from our witnesses today on how Congress can support the U.S. Weather Enterprise through Federal investments in weather research that will benefit all Americans.

[The prepared statement of Chairwoman Sherrill follows:]

Good morning, and welcome to today's hearing on the future of weather research. I am especially pleased to welcome all our esteemed witnesses to today's hearing in person after two years of virtual and hybrid testimony.

Weather forecasting plays an integral role in society, and a crucial role in protecting lives during extreme weather events. You may not realize it, but each and every American benefits from the federal investments made to support the National Weather Service every day. Whether you are using a weather app on your phone, or watching your local meteorologist on the evening news, these products and services depend on federal weather data. Weather forecasting is consistently relied on to guide planning across the US—whether it's deciding whether to take an umbrella on a work commute, planning an outdoor gathering with friends and family, or determining a seasonal crop plan.

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Chairwoman SHERRILL. The Chair now recognizes Ranking Member Bice for an opening statement.

Mrs. BICE. Thank you, Chairwoman Sherrill, and thank you to our entire panel of witnesses for taking the time to share your expertise with us this morning.

Weather information does more than just help us decide how many layers to wear or whether to bring an umbrella. Forecasts based on accurate information are our No. 1 tool in protecting the life and property during severe weather events. That's extremely important because the United States experiences more extreme weather events than any other country. According to the National Weather Service, a typical year in the United States sees 26,000 thunderstorms, a few of which I see in my community weekly, 5,000 floods, 1,300 tornadoes, and six Atlantic basin hurricanes.

Luckily, academia, government, and industry have come together in collaboration to improve the timely delivery and overall accuracy

of weather products and services. Collectively known as the U.S. Weather Enterprise, each sector—public, private, and academic—plays a critical role in understanding, observing, forecasting, and helping warn communities of danger.

The largest improvement to weather forecasting can be directly attributed to both basic and applied research. Collaboration across the weather enterprise is critical to conducting this research and translating it so it can be successfully deployed on a commercial scale. For example, atmospheric data collected from a satellite needs unique computer modeling and processing power to be useful. And the final forecast or output product must integrate behavioral and social science to make sure people fully understand it and its impact. No one sector can develop or do all of this on their own. That's why transitioning research into operations requires buy-in and collaboration from everyone. It cannot be a competition amongst ourselves.

To aid in our forecasting goals, there are countless emerging technologies that can and should be deployed. Automated surface vehicles and gliders in the ocean, drones in the sky, and advanced radar systems on the ground all have the potential to collect data that can supplement current Federal efforts. Pursuing this research and subsequent commercialization will be invaluable to the United States and our communities. First, it will help us catch up to the European Union, which continues to outperform us with more accurate forecasting models.

Second, it will support economic growth. Essential pillars of our economy are dependent on knowing what the weather will be. For example, we need solar and wind data for renewable energy production; precipitation information for ag production; water management analysis for urban communities; and accurate predictions for road, marine, and aviation transportation. These are all areas of increased investment, and all of them require forecasts for safe and efficient operation.

I can't think of a better panel to address this critical topic. We have representatives from academia, the private sector, and professional societies. I want to especially extend my warmest welcome to Dr. Fred Carr, a fellow Oklahoman and Professor Emeritus at the University of Oklahoma (OU) with the newly minted women's national championship softball team. Although I am an Oklahoma State fan myself, I will admit OU is widely recognized as a national leader in meteorology and has made vital contributions in this field. In fact, the entire State of Oklahoma has long been viewed as the center of weather advancement in the United States, and I look forward to hearing how the National Weather Center in Norman is continuing to lead critical research and development.

Again, I want to thank the witnesses for being here today, and I look forward to your testimony. With that, I turn the chair back over to Chairwoman Sherrill.

[The prepared statement of Mrs. Bice follows:]

Thank you, Chairwoman Sherrill, and thank you to our entire panel of witnesses for taking the time to share their expertise with us this morning.

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In fact, the entire state of Oklahoma has long been viewed as the center of weather advancement in the U.S. and I look forward to hearing how the National Weather Center in Norman is continuing to lead critical research and development.

Again, I want to thank our witnesses for being here today and I look forward to each of your testimony. Thank you, Chairwoman Sherrill, I yield back the balance of my time.

Chairwoman SHERRILL. Thank you. And we are honored to have the Full Committee Ranking Member Mr. Lucas with us today. The Chair now recognizes Ranking—the Ranking Member for an opening statement.

Mr. LUCAS. Thank you for holding today's hearing on this important topic, Chairwoman Sherrill.

Since I became the Ranking Member of this Committee, I have time and again stated that the work we do on weather forecasting is as important as any topic before us. Protecting life and property, helping first responders anticipate maximum weather events, or ensuring that farmers and ranchers know when to best plant crops are only a few of the reasons having accurate weather forecasts is invaluable. And we can only have accurate weather forecasts if we continue to invest in resources in researching weather patterns.

The Ranking Member of the Subcommittee and I are both honored to represent Oklahoma, home to some of the most important weather research occurring today. The National Weather Center, located in Norman, brings together NOAA (National Oceanic and Atmospheric Administration) researchers, the University of Oklahoma faculty, and local weather forecasters under one roof. This collaboration is an important model for how NOAA research should operate.

Additionally, Oklahoma is home to the Nation's premier mesonet, which provides real-time data thanks to a series of small but powerful monitoring stations across the State. The mesonet has been a valuable resource for farmers, ranchers, first responders, and weather forecasters for more than 25 years, and I believe our mesonet should serve as a model for other weather observation systems across the country.

It is with this background that I am proud to sponsor the *Weather Research and Forecasting Innovation Act,* more commonly known as the *Weather Act.* This legislation, signed into law by President Trump in April 2017, was the most significant weather-related legislation to become law in 25 years. This legislation helped redefine NOAA's weather research priorities in recent years and also helped spur innovation by creating a pilot program which directed the utilization of commercially purchased data in NOAA's weather models.

The *Weather Act* is due for reauthorization at the end of September 2023. Though that is more than a year away, I consider today's hearing to be a kickoff in our reauthorization process and encourage our witnesses to frame their recommendations with this in mind.

In December of 2020, Congress directed NOAA's Science Advisory Board to commission a report on future priorities in weather research. This report, completed in December 2021, utilized some of the finest minds across the weather enterprise. This report contains many recommendations, ranging from improving Earth-system modeling to increasing NOAA's computing capacity. These recommendations should inform how we approach reauthorizing the *Weather Act.*

Today's hearing is important because it provides a starting point for us in discussions about what areas where we have improved our knowledge of weather research, as well as gaps we need to address in the future.

I want to thank the witnesses for sharing their expertise, and I look forward to a very productive discussion.

And before I yield back, just a personal moment to share my sincere feelings with the Chairman about the loss of one of our colleagues. Nothing can hurt more. And with that, I yield back, Madam Chair.

Chairwoman SHERRILL. Thank you so much, Mr. Lucas.

[The prepared statement of Mr. Lucas follows:]

Thank you for holding today's hearing on this important topic, Chairwoman Sherrill.

Since I became the ranking member of this committee, I have time and again stated that the work we do on weather forecasting is as important as any topic before us.

Protecting life and property, helping first responders anticipate extreme weather events, or ensuring that farmers and ranchers know when best to plant crops are only a few of the reasons having accurate weather forecasts is invaluable. And we can only have accurate weather forecasts if we continue to invest resources in researching weather patterns.

The ranking member of the subcommittee and I are both honored to represent Oklahoma, home to some of the most important weather research occurring today. The National Weather Center, located in Norman, brings together NOAA researchers, University of Oklahoma faculty, and local weather forecasters under one roof. This collaboration is an important model for how NOAA research should operate.

Additionally, Oklahoma is home to the nation's premier Mesonet, which provides real- time data thanks to a series of small, but powerful monitoring states across the state. The Mesonet has been a valuable resource for farmers, ranchers, first responders and weather forecasters, for more than 25 years, and I believe our Mesonet should serve as a model for other local weather observation systems across the country.

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Today's hearing is important because it provides a starting point for us in discussions about areas where we have improved our knowledge of weather research as well as gaps we need to address in the future.

I thank our witnesses for sharing their expertise with us and I look forward to a productive discussion. Thank you and I yield back.

Chairwoman SHERRILL. At this time, I'd like to introduce our witnesses. I'm pleased to introduce a fellow New Jerseyan Dr. Scott Glenn as our first witness. Dr. Glenn is a Board of Governors Professor of Marine and Coastal Sciences and Co-Director of the Center for Ocean Observing Leadership at Rutgers University. Dr. Glenn's research has focused on the development of remote and autonomous technologies for ocean observing in extreme environments, the modeling of coupled ocean atmosphere systems, and improving the forecasting of hurricanes. Dr. Glenn is one of the NOAA SAB (Science Advisory Board) PWR report co-leads.

Our next witness is Dr. Brad Colman. Dr. Colman is the Director of Weather Strategy for the Bayer Climate LLC, and President-Elect of the American Meteorological Society (AMS). At Bayer, he coordinates across multiple divisions to set weather priorities and works with scientists, engineers, and vendors to deliver critical environmental information across Bayer's global agriculture industry. Prior to joining the private sector, Dr. Colman had a nearly four-decade-long career with NOAA, ranging from a forecaster to NOAA NWS Lab Director. Dr. Colman is also one of the NOAA SAB PWR report co-leads.

Our next witness today is Dr. Frederick Carr. Dr. Carr is currently the McCasland Foundation Presidential Professor Emeritus and Director Emeritus in the School of Meteorology at the Univer-

sity of Oklahoma. His research interests include numerical weather prediction, data assimilation, synoptic mesoscale and tropical meteorology, and use of new observing systems. Among his wide variety of professional activities, Dr. Carr was the President of the American Meteorological Society in 2016, served on the AMS's Executive Committee from 2015 to 2019, and is a Fellow of the AMS in addition to currently chairing its Committee on Ethics.

Our final witness is Dr. Kevin Petty. Dr. Petty is the Vice President of Weather and Earth Intelligence at Spire. Dr. Petty oversees science and engineering associated with the delivery of weather-related products and solutions, as well as the development of new observations that support our understanding of the planet. Before joining Spire, Dr. Petty was the Director of Science and Weather—and forecast operations at The Weather Company, an IBM Business. He has also worked as a Project Scientist and Scientific Program Manager with the National Center for Atmospheric Research, and Senior Meteorologist for the National Transportation Safety Board.

If there are Members who wish to submit additional opening statements, your statements will be added to the record at this point.

[The prepared statement of Chairwoman Johnson follows:]

Good morning, everyone. I want to thank Chairwoman Sherrill for holding today's hearing on a very important topic: the future of weather research. I also want to welcome our witnesses and I look forward to your testimony.

The U.S. Weather Enterprise-the public sector, the private sector, and academia-have made considerable strides in improving forecasts over the past few decades. However, we must not become complacent and assume this progress is enough-it is not.

As many of you know, high-temperature records are being shattered across the southern U.S. Last Saturday, temperatures in my district and the surrounding areas in the DFW Metroplex exceeded 100 degrees Fahrenheit for the first time in 2022. The last time we exceeded 100 degrees this early in the year was 2010.

We have often discussed in this Committee how climate change is leading to more frequent and intense extreme weather events.

From 2017 to 2021, the cumulative cost of billion-dollar or greater weather and climate disasters was nearly three-quarters of a trillion dollars. And last year alone, there were twenty major disasters resulting in approximately 145 billion dollars of damages. These damages, and the human toll, would have been would far greater if we hadn't previously invested in weather research.

It is essential that we have the necessary resources and capabilities to accurately predict these weather events, as well as to prepare our communities for them.

In order to better understand what is needed to support American excellence in weather forecasting, we turned to the experts.

In 2019, Congress charged NOAA's Science Advisory Board (SAB) to assess the needs for weather research. Specifically, the SAB was charged with identifying the Federal investments in weather research and forecasting needed over the next decade. As a result, NOAA's SAB produced the Priorities of Weather Research report in December of 2021.

We are fortunate to have four experts in weather research testifying this morning, which includes the NOAA SAB report's co-leads. This report could not be better timed. In 2022, we have to shift the paradigm around weather forecasting in the U.S.

We must make decisions about forecasting improvements with the needs of the most vulnerable communities at the forefront, and not as an afterthought. This will require robust and consistent funding from Congress. This Committee will have a key legislative and oversight role to play.

Today's hearing is a continuation of this Committee's work to discuss topics pertinent to improving U.S. weather forecasting.

The major themes in this report align with topics we have often discussed on this Committee. The case has been made many times over for the need to improve weather forecasting in the U.S.

What is left for Congress to do is provide clear direction, and commensurate funding, to support weather research improvements. We cannot afford to underinvest in weather research. The time to act is now.

I am looking forward to hearing from our esteemed panel of witnesses what the Federal government must prioritize in weather research. I hope today's hearing will serve as a roadmap for the future of NOAA's National Weather Service and the Weather Enterprise. With that, I yield back.

Chairwoman SHERRILL. Thank you to all of our witnesses for joining us today.

And at this point, we will begin our first round of questions. I'll now recognize myself for five minutes. Oh, sorry. So I'm going to recognize the witnesses in the order I introduced them. As you recall, you each have five minutes for your opening statements.

So we'll start with Dr. Glenn.

TESTIMONY OF DR. SCOTT GLENN, BOARD OF GOVERNORS PROFESSOR CENTER FOR OCEAN OBSERVING LEADERSHIP OF THE DEPARTMENT OF MARINE AND COASTAL SCIENCES, RUTGERS UNIVERSITY

Dr. GLENN. Chairwoman Sherrill, Ranking Member Bice, Ranking Member Lucas, Members of the Subcommittee, I sincerely thank you all for the opportunity to speak today on the future of weather research and forecasting for our Nation. My name is Scott Glenn. I'm a Professor at Rutgers, the State University of New Jersey. And I'm—I was one of the co-leads for the NOAA Science Advisory Board report on the Priorities for Weather Research, often referred to as the PWR report. The views that I'm sharing today are my own and not those of Rutgers or NOAA.

The PWR report was produced by over 150 subject matter experts from across the weather enterprise. Through a consensus approach, experts from multiple sectors and disciplines came together to provide policymakers the information necessary to prioritize Federal investments in weather research and forecasting over the next decade.

PWR is an urgent call to action. That urgency is driven by the increasing frequency of extreme weather events that cause hundreds of deaths and hundreds of billions of dollars of damage each year. It is driven by the need to develop a vibrant economy that leverages weather information into competitive advantages, and it is driven by the need to support equity and environmental justice across our Nation.

The PWR report responds by documenting priority investments across the three pillars of the weather enterprise: observations and data assimilation, forecasting, and information delivery.

These pillars are built on the strong foundational elements of the weather enterprise itself, the people trained through work force development, the high-performance computing (HPC) for operations and research, and the world's best science. Taken together, the pillars and their foundational elements support our shared goal of a weather-ready nation.

The results of the PWR study are 11 priority areas for investment, 33 recommendations and envisioned outcomes, and 102 specific critical actions to achieve these goals. Acting on these rec-

ommendations will be transformational for NOAA, the weather enterprise, and the people we serve.

To illustrate how this broad range of recommendations work together to support specific needs, PWR produced five narrative themes. One of those themes is high-impact weather. One example within this theme, the example I've studied my entire career, is hurricanes. Hurricanes are among the most destructive weather events on Earth. Since 1980, hurricanes have caused over $1 trillion in damage in the United States, more than all other weather and climate billion-dollar disasters combined.

In my home State of New Jersey, over 80 percent of the billion-dollar disaster damage was caused by hurricanes. Having lived through the intense winds and flooding caused by Hurricanes Floyd, Irene, Sandy, Isaias, and Ida, I personally know the value of the good forecasts from our trusted National Hurricane Center.

Through disaster supplemental appropriations provided by Congress that support hurricane observations and research, our science community has also learned what we can do to help make forecasts even better. Our team has pioneered new technologies for ocean observing in extreme conditions. We have used those technologies to develop a fundamentally new understanding of how the atmosphere and ocean are coupled and can rapidly co-evolve as hurricanes approach my home State. And we have helped transition both observation and modeling improvements into operational systems for NOAA, the Coast Guard and the Navy.

Fundamental to those advances is continuing NOAA's transition to an Earth system modeling approach. This will require observations of the atmosphere and the ocean below. It will require high-performance computing for operations and research. And it will require collaboration that crosses line offices and sectors. All of the investment categories and approaches are outlined in the PWR report.

As one specific example, hurricane forecasting in the United States has long benefited from Federal investments in the Hurricane Forecast Improvement Program. However, success is currently being limited, not by vision, but by support. In my written testimony I've outlined three ways hurricane forecast improvements are being limited and what can be done about it.

In conclusion, PWR provides a framework for transformation. Trends in extreme weather events lend urgency. I urge this Committee and Congress to act upon the recommendations outlined the PWR report so that together we can build and are able to serve the needs of our Nation. Thank you.

[The prepared statement of Dr. Glenn follows:]

Written Testimony of Dr. Scott Glenn
Board of Governors Professor of Marine and Coastal Sciences
Co-Director of the Center for Ocean Observing Leadership
Rutgers, The State University of New Jersey

Before the Subcommittee on Environment
Committee on Science, Space, and Technology
U.S. House of Representatives

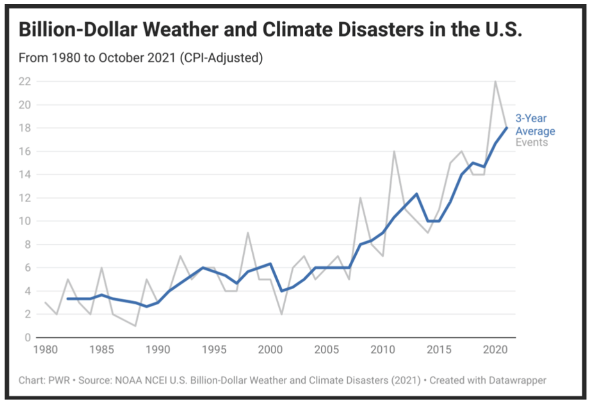
Hearing on "What's the Forecast: A Look at the Future of Weather Research"
Tuesday, June 14, 2022

Congresswoman Sherrill, Ranking Member Bice, members of the Subcommittee, I sincerely thank you for the opportunity to speak to you today about the future of weather research and forecasting for our nation.

My name is Scott Glenn. I have been a professor at Rutgers, The State University of New Jersey, for over 30 years, and I was one of the co-leads for the NOAA Science Advisory Board Report on the *Priorities for Weather Research*, often referred to as the PWR Report (NOAA SAB 2021; 2022). The views that I am sharing today are my own, and not those of Rutgers or NOAA.

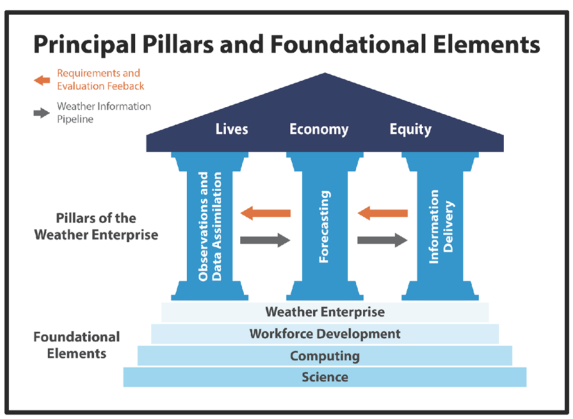
The PWR Report was co-led by an industry meteorologist and an academic oceanographer, underscoring both the value of cross-sector partnerships within the Weather Enterprise, and the critical need to accelerate the positive gains we have already made with an Earth System Science approach. The PWR report was produced by over 150 subject matter experts from across the Weather Enterprise. Through a consensus approach, government, industry and academic experts from multiple disciplines came together to provide policymakers the information necessary to prioritize federal investments in weather research and forecasting over the next decade.

PWR is an urgent call to action. That urgency is driven by the increasing frequency of extreme weather events that cause hundreds of deaths and hundreds of billions of dollars of damage annually (PWR Report Figure 3 reproduced below). It is driven by the need to develop a vibrant economy that leverages weather information into competitive advantages rather than blames the weather for economic losses. And it is driven by the need to support equity and environmental justice across our nation.



PWR Report Figure 3: *Annual (gray) and 3-year running average (blue) number of U.S. Billion Dollar Weather and Climate Disaster Events 1980-2021*

The PWR report responds by documenting priority investments across the three pillars of the Weather Enterprise: (1) observations and data assimilation, (2) forecasting, and (3) information delivery (PWR Report Figure 5 reproduced below). These pillars are built on the strong foundational elements of the weather enterprise, workforce development, high performance computing, and the world's best science. Taken together, the pillars and their foundational elements support our shared goal to be a more Weather Ready Nation, which can save lives and protect critical infrastructure, promote a vibrant weather-informed economy, and achieve environmental justice.

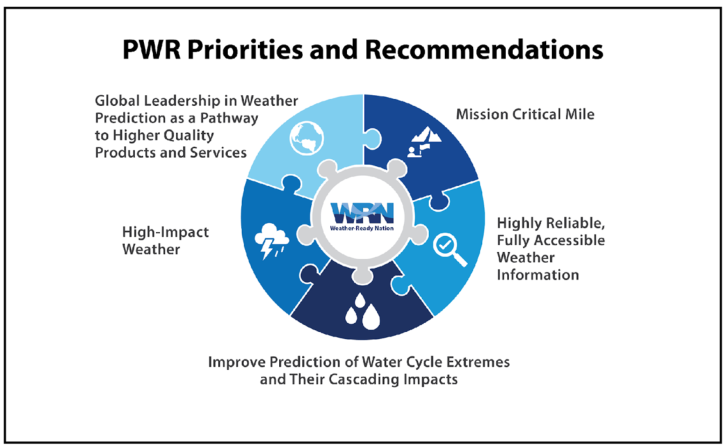


PWR Report Figure 5: *Priorities for Weather Research Strategic Framework*

The results of the PWR study are 11 Priority Areas for investment spread across the three pillars and the four foundational elements. Within these Priority Areas, PWR developed 33 Recommendations, and 102 specific Critical Actions to achieve their goals. Acting on these recommendations would be transformational for NOAA, our Weather Enterprise, and the people we serve.

Realizing that implementation of a comprehensive suite of priority recommendations will take time, PWR provides a roadmap highlighting 10 immediate first steps in the categories of research and development, infrastructure, actions and impacts, and the continued development of the prioritization process. These first steps were identified by their ability to promote significant advances, close significant gaps, or enable other recommendations when properly sequenced.

In addition, PWR produced five Narrative Themes to illustrate broad scientific and societal benefits that could be delivered by a focused and well-supported Weather Enterprise. One of these themes is High-Impact Weather. An example under this theme, one in which I have studied throughout my professional career, is hurricanes.



PWR Report Figure 6: *Narrative Themes supporting a Weather-Ready Nation*

Hurricanes are among the most destructive weather events on Earth. Since 1970, the world's top six economic losses from weather, climate and water extremes were hurricanes in the U.S. (WMO, 2021, Table 1, Page 18, $490 Billion in damage for 6 events). Since 1980, hurricanes have caused over $1 Trillion in damage in the U.S., more (52 percent) than all other weather and climate billion dollar disasters combined (NOAA, 2022a). In my home state of New Jersey, over 80 percent of the billion dollar disaster damage was caused by hurricanes (NOAA, 2022b).

I have been a storm researcher for over 40 years. Working with faculty colleagues at Rutgers, our government and industry partners, and our students (some of whom have gone on to work at NOAA), we have pioneered new ruggedized, autonomous technologies for ocean observing in extreme conditions. We have developed a fundamentally new understanding of how the atmosphere and ocean can rapidly co-evolve as hurricanes approach my home state of New Jersey (e.g., Glenn et al., 2016). And we have helped transition both observing systems and model improvements into operational systems for NOAA, the Coast Guard, and the Navy.

Having lived through the intense winds and flooding caused by Hurricanes Floyd, Irene, Sandy, Isaias and Ida, I personally know the value of a good forecast from our trusted National Hurricane Center. Through disaster supplemental appropriations provided by Congress that support hurricane observations and research, our science community has also learned what we can do to help make those forecasts even better. Fundamental to those advances is continuing NOAA's transition to an Earth System Modeling approach, supported by observations of both the atmosphere and the ocean below, and implemented across NOAA line offices and through cross-sector partnerships. All of these investment categories and approaches are outlined in the PWR Report.

For nearly 15 years, hurricane forecasting in the U.S. has benefited from federal investments in the Hurricane Forecast Improvement Program (HFIP), which is designed to rapidly transition high readiness level research into operations that improve hurricane forecasts and warnings. Many of the documented hurricane forecast improvements can be directly attributed to Congressional investments in HFIP activities. However, the success of HFIP, and the broader Weather Enterprise, is currently being limited, not by vision, but by support. The following are three ways HFIP has been limited:

1. HFIP is supported at approximately half the level required to fully implement its strategic plan. Investments are currently weighted toward the early part of the Weather Enterprise, such as observations and modeling. This comes at the expense of other areas, particularly improvements to information delivery. This partial level of support is not uncommon for valuable NOAA programs.

   What can be done? Leveraging experience across NOAA line offices (e.g., OAR for basic and applied Earth System research, NWS and NOS for an Earth System approach to observations and modeling, NESDIS for additional satellite data, …) can promote efficiencies and accelerate progress. But this will still require that both HFIP, and the leveraged components within NOAA, be fully supported in the sustained and coordinated manner required to accelerate progress.

2. Having high readiness level research available for rapid transition by HFIP requires a significant pool of well-supported basic and applied research available to be elevated in readiness level and accelerated into operations. For example, the basic and applied research required in understanding air-sea interactions and rapid intensity change (both rapid intensification and rapid weakening), in developing new data assimilation

techniques for coupled systems, and in improving coupled Earth System Models (ESM), will deliver benefits to a much broader community than just hurricane forecasting. It will contribute to global leadership in all applications of weather prediction.

What can be done? Leveraging the disaster supplemental support that accelerated development of the Hurricane Analysis and Forecast System (HAFS) within the framework of the Unified Forecast System (UFS), with community involvement to be enabled through the Earth Prediction Innovation Center (EPIC), is an existing collaborative framework waiting to be populated with academic and industry researchers and their students. The open science community that develops in this curated workspace will also require research-level High Performance Computing resources to succeed.

3. Once high readiness level research is transitioned, there has to be an operational home with the capacity to sustain the upgrades. This again includes the need for additional operations-grade High Performance Computing resources to run upgraded Earth System Models and coupled data assimilation schemes. It also needs to include operational support for the additional atmosphere and ocean observations required for assimilation in the coupled forecast models. Currently there are significantly less ocean observations assimilated in the global ocean models than in the atmosphere, mainly due to the challenges in subsurface ocean data acquisition and the timely transfer of data to operational centers.

   What can be done? One example is the collaborative approach of supplementing year-round Argo ocean profiling float data with seasonally deployed underwater hurricane gliders in critical locations. The success of this approach has been demonstrated by the NOAA-led U.S. Integrated Ocean Observing System (IOOS), NOAA's Office of Oceanic and Atmospheric Research, and their external partners, leading to a dramatic increase in the available ocean data during the 2018 through 2021 hurricane seasons. The IOOS Regional Associations implementing much of the hurricane glider fleet are NOAA-certified partnerships between government, tribal, academic and industry groups with the regional knowledge and experience to efficiently implement a nationally coordinated response. Currently, any entity operating an underwater glider for any purpose can share its data through the IOOS system, thereby enabling even broader contributions to improved hurricane forecasts. This IOOS capability has been leveraged by the energy companies in the Gulf of Mexico, the offshore wind industry in the Mid Atlantic, and by the Navy for training exercises in U.S. waters, so that each group can accomplish their own mission goals while also seamlessly contributing to improved hurricane forecasts. But unfortunately, the current hurricane season is between disaster supplementals, greatly reducing the anticipated size of the 2022 hurricane glider fleet, and leaving our nation's coasts with reduced coverage during what is expected to be an above-average North Atlantic hurricane season (NOAA News-Release, 2022). This is a prime example of the PWR recommendation to complete the build-out of the observational networks required to support the new Earth System Models.

In conclusion, the PWR Report provides a framework that could transform NOAA and positively impact NOAA's many partners that comprise the Weather Enterprise. The growing challenges of supporting a Weather Ready Nation during a time of increasing extreme weather events lends urgency to the PWR recommendations. Today I have highlighted one example of how the PWR recommendations positively impact an issue that I am most familiar with – improving hurricane forecasts. There certainly are other issues, and you will hear about some of them from other speakers today. I urge this Committee and Congress to act upon the priority recommendations outlined in the PWR Report so that NOAA, and the Weather Enterprise, will be enabled to better serve the needs of our nation.

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Scott Glenn – Short Biography

Scott Glenn began his career in storm research at the Massachusetts Institute of Technology and the Woods Hole Oceanographic Institution Joint Program where he received his Sc.D. in 1983. He worked in hurricane and ocean observations, modeling and forecasting for Shell Development Company until 1986, and transitioned the U.S. Navy's first dynamical ocean forecast model to operational use while working at Harvard University in 1989. Since joining Rutgers in 1990, his research has focused on the development of remote and autonomous technologies for ocean observing in extreme environments, the modeling of coupled ocean-atmosphere systems, and improving the forecasting of hurricanes. He currently is a Board of Governors Professor of Marine and Coastal Sciences at Rutgers, The State University of New Jersey, where he is the Co-Director of the Center for Ocean Observing Leadership. Honors include U.S. Professors of the Year for New Jersey by the Carnegie Foundation, the Office of Naval Research Collaboration Award for supporting the Navy warfighter, the first transatlantic underwater glider displayed at the Smithsonian, the Oceanography Award from the International Society for Underwater Technology in London, and being named a Fellow of the international Marine Technology Society.

Chairwoman SHERRILL. Thank you, Dr. Glenn. Next, I recognize Dr. Colman for five minutes.

TESTIMONY OF DR. BRADLEY COLMAN, PRESIDENT-ELECT OF THE AMERICAN METEOROLOGICAL SOCIETY; DIRECTOR OF WEATHER-STRATEGY, BAYER & THE CLIMATE CORPORATION

Dr. COLMAN. Good morning. Chairwoman Sherrill, Ranking Member Bice, Committee Ranking Member Lucas and Members of the Subcommittee, thank you for this hearing and for inviting me to speak with you today about the future of weather research and forecasting. My name is Brad Colman. I'm currently the Director of Weather Strategy for Bayer's Climate Corporation, President-Elect of the American Meteorological Society, and co-lead with Dr. Glenn on the PWR report. The views I am sharing are my own and not those of Bayer or NOAA.

I want to thank the Subcommittee for your support of the *Weather Act* and the *NIDIS Reauthorization Act.* These acts have been highly impactful and provide critical groundwork for many of the PWR report priorities.

My testimony is based on four decades with NOAA, followed by nearly a decade in private industry. I worked across multiple levels at NOAA from Forecaster to Lab Director. At Bayer, we, like many other businesses, leverage NOAA's array of products, which supplement our own data and in-house expertise to serve our leading global agricultural business. I have seen NOAA's impact from the inside and out, and I have complementing perspectives of both its past and its potential future value.

Today, we face sobering weather-related statistics. The Nation is suffering from increasing billion-dollar disasters and the loss of hundreds of Americans annually, all despite continually improving forecasts and warnings. Five-day forecasts are as good or better than 3-day forecasts were at the turn of the century. Forecast skill is now extending into the second week. Hurricane track forecasts at day 5 are now as good as a 2-day forecast was just in 1990. The benefits to the public, transportation, and private industry are remarkable.

These gains were not achieved through singular investments, major breakthroughs, or by a single sector of the weather enterprise. Federal investments have been instrumental including the 88D radar network, next-generation satellites, and the National Weather Service's Weather-Ready Nation program. The academic and private sectors have made equally critical contributions. If done correctly, with planning and coordination across all sectors, the weather enterprise can extend this proven track record well beyond the next decade.

I now want to discuss a core section of the report, critical first steps. This section lists 10 actions essential to the success of any comprehensive Federal investment plan. They are a subset of all recommendations in the report and fall into one of four areas: research and development, infrastructure, actions and impacts, and NOAA prioritization and investment.

The first area, research and development, includes Earth system modeling, data assimilation, and social and behavioral sciences. As

forecasting skill has increased, a significant gap has grown between weather information produced and known by forecasters and what is understood and acted upon by public and emergency management communities. Addressing this gap is especially critical for historically underserved and socially vulnerable populations. Investments in this area need to be significantly increased in order to achieve the full benefit from other investments in the weather information pipeline.

I do not have time to speak to the area of infrastructure, which includes data assimilation, high-performance computing, and Earth system observing networks.

The actions and impacts area includes reanalysis and reforecasting, high-impact weather and water cycle extremes. Reanalysis and reforecasting in support of operational numerical model development is critical and it needs immediate attention at NOAA. In fact, the launch of their first Earth system model scheduled for 2026 cannot be successfully implemented without this gap being addressed.

The final area is NOAA prioritization and investment. At times, NOAA has struggled to align internal priorities and partner with external groups. This has likely reduced their overall impact. As such, increased Federal investments in NOAA National Weather Service programs would greatly benefit from NOAA having improved methods to assess, balance, and align these investments. Additionally, NOAA stands to benefit by increased partnerships with a broader weather enterprise. A strong private industry can provide value in the form of otherwise unavailable data, products, and services to Federal agencies that in turn accelerate the overall research and innovation through partnerships, including with the academic sector. Successes in this area are wins for the weather enterprise and wins for the Nation.

In closing, this is a critical time. Our Nation is increasingly challenged by weather extremes and climate change impacts. The benefits of executing a successful PWR plan would be transformational. Together, we need to build off past successes, learn from past challenges, and work together toward a better prepared weather-ready nation.

Thank you, and I look forward to your questions.

[The prepared statement of Dr. Colman follows:]

Written Testimony of Dr. Brad Colman
Director of Weather Strategy, Bayer / Climate LLC
Seattle, Washington

Before the Subcommittee on Environment
Committee on Science, Space, and Technology
U.S. House of Representatives

Hearing on "What's the Forecast: A Look at the Future of Weather Research"
Tuesday, June 14, 2022

Congresswoman Sherrill, Ranking Member Bice, and members of the Subcommittee, thank you for inviting me to speak to you today about the future of weather research and forecasting for our nation.

My name is Brad Colman. I am currently the Director of Weather Strategy for Bayer / Climate LLC, President-Elect of the American Meteorological Society, and one of the co-leads for the NOAA Science Advisory Board's Report on the Priorities for Weather Research, or the PWR Report. The views that I am sharing here are my own, and not those of Bayer or NOAA.

I applaud the sub-committee for recognizing the importance of Federal investments in weather research, forecasting, and dissemination as a means to mitigate the impact of weather and climate extremes on our society. This is a topic that is increasingly critical to the citizens and businesses of the United States and beyond. We are faced with the sobering statistics of increasing weather and climate impacts and disasters suffering losses in the billions of dollars multiple times each year and losing hundreds of American lives with increasing frequency.

My testimony is based upon a nearly four-decades long career with NOAA (ranging from being a forecaster in Juneau, Alaska, to a NOAA/NWS Lab Director, in Washington, DC) that has been followed by nearly a decade of working in private industry (at Microsoft and Bayer). Over my career, I have had the great fortune of working in positions within NOAA that have included helping to implement a modernization of the weather service and introduce research positions as a critical component of field offices across the country. I have seen first-hand in my lifetime the increase in value of weather information and forecasts, which has been nothing short of remarkable. As such, I am particularly proud of what the weather enterprise (a close and critical collaboration between public, private, and academic sectors) has delivered.

Indeed, the weather enterprise has an exceptional and proven track record. The dramatic results derive from years of investment from the Federal government, along with tremendous contributions and advances from the academic and private sectors. NOAA has served as a solid foundation guided by its mandated mission to protect life and property and better the U.S. economy.

When I started college, a weather forecast was skillful for only a few days and often more likely the source for a joke or a complaint, than considered in a decision to evacuate or take cover.

Today, 5-day forecasts are as good or better than a 3-day forecast was at the turn of this century, and skillful weather forecasts extend well into the second week. For just a moment, consider the value this kind of improvement has brought to Americans and American businesses. People can now better plan their activities for the week, industry can make critical business decisions that dramatically increase their profit margins, and emergency managers can make earlier and better decisions about when and who to evacuate in their efforts to better protect Americans and their property.

These gains were not achieved through singular investments, or major breakthroughs, rather they were developed through continuous investment across many fronts, and hard work and collaboration across the weather enterprise over these past decades. Let me call out a few past examples (and these are only a few, there are many others) that we are all likely familiar with to underscore this linkage between significant Federal investments and proven benefits to our country.

A great example is the investment that was made to install and maintain the NOAA/FAA/DOD WSR-88D national radar network. As a result, minutes have been trimmed off the lead time of warnings for severe thunderstorms and tornadoes. The radar data are assimilated into weather prediction models and contribute to improvements in weather forecast skill. Each of us is now able to enjoy phone apps from the weather industry that provide short-term forecasts that were unimaginable just a few years ago. For example, they provide each of us with minute-by-minute updates on when rain or snow is going to stop or start – essentially down to our neighborhood or exact location. The benefits to the public, agriculture, transportation, and other industries have been immense.

Another example, to which I briefly alluded to previously, took place between 1989 and 2000, when the nation invested approximately $4.5 billion to implement the Modernization and Associated Restructuring (MAR) of the NWS. As part of that project, new observational and computational systems were planned and deployed, including the 88D network. Critically, NWS field offices around the country were redefined around new models for observing, forecasting, and service delivery that allowed them to capitalize on the investments in these new systems. I had the good fortune of being part of that restructuring and was one of the first Science Operation Officers introduced into forecast offices around the country. I and my colleagues helped introduce and demonstrate ways in which new technological advances could be implemented within NOAA's production systems and allow for delivering longer range, yet more targeted, forecasts. The entire NWS workforce was restructured around these concepts, with targeted investments in training and recruitment that gave the forecasters the skills and knowledge necessary to implement what was then a modernized NWS.

As forecast skills increased, their potential value increased, yet it was soon recognized that the optimal value of the weather information to the stakeholders was not being achieved. In other words, there was a growing gap between the information being produced by the forecasting process and the value gained by the end users. As this was becoming more apparent, efforts to address this gap occurred both on the public side and within private industry. NOAA/NWS turned their field office focus to communication and support through their Impact Based Decision Support Services program, which provided the interpretation, expressions of

confidence, and details necessary to ensure that not only were the NWS's forecasts increasingly accurate, but they were also consumable and actionable, and resulted in the right actions being taken. Equally, private industry made great strides in adding customized value to the NOAA foundation and increasingly developing additional internal capacity to better serve the U.S. and global economies.

As remarkable as these advances have been at saving countless lives, enabling the protection of infrastructure, and mitigating business losses due to weather impacts, we have likely fallen short of where we could have been, and more work still needs to be done. In fact, there is some evidence that the progress in some areas we have all enjoyed and benefited from is slowing (e.g., the skill of medium-range numerical model forecasts). Fortunately, the weather community feels strongly that if done correctly, the weather enterprise can build upon this overall remarkable success story and extend its proven track record through and beyond the next decade. These new benefits would be delivered at a critical time as our Nation is increasingly challenged by weather extremes and climate change impacts.

The PWR report (NOAA Science Advisory Board, 2021) lays out a comprehensive plan that has the potential to be transformational over this coming decade if fully executed. The report identifies three pillars (observations, forecasting, and information delivery), along with several foundational elements (science, computing, workforce development, and the weather enterprise), as being critical to achieving the gains in the value in weather information that are believed possible and critical over this coming decade. Similar to how gains over the past decades were achieved, the report highlights that future advances will be best enabled by the continued investments across multiple fronts. For example, gains in observations must be balanced by better data assimilation and improved numerical models. In turn, these investments need to be informed by societal needs and benefits. Finally, research and investment in the development and delivery of weather information are necessary if related efforts are to keep pace with the scientific and forecast advancements and ultimately improve the ability to protect lives and property, expand the communities served with relevant weather information, and promote economic vitality at this critical time of rapidly changing weather trends and extremes.

I now want to draw your attention to, and focus on, a critical part of the PWR report, namely the section on critical first steps. This section is a collection of ten actions or recommendations that stand out as critical to the success of any plan to move the weather enterprise forward. They are a subset of all recommendations and critical actions identified by the PWR Study Team.
One of three factors drove the selection of each: (1) an ability to deliver immediate benefit (low risk/high reward); (2) necessary to close a critical gap or shortfall; or (3) first in a temporal dependency across multiple actions. These steps were further clustered into four areas including: Research and development, Infrastructure, Action and impacts, and NOAA prioritization and investment. These critical first steps are also highlighted in the PWR Report in Brief (NOAA Science Advisory Board, 2022). I will now briefly call your attention to efforts within each of these four areas.

RESEARCH & DEVELOPMENT: This first area identifies three specific recommendations or actions. The first is an immediate focus on the development of an Earth System Modeling (ESM) framework approach to improve forecast accuracy and lead time. I mentioned earlier that there is

some slowing of forecast skill improvements across all major global modeling efforts, including the European Center for Medium Range Forecast and NOAA's Global Forecast System (GFS). While there are several candidate explanations for this slowing, one possibility is that we are reaching the limits of an atmosphere-focused framework. Moving to a fully coupled earth system that includes oceans, the cryosphere, and improved land surface models, is needed to help extend skillful forecasts to longer lead times and deliver greater benefit. Furthermore, the ESM framework is critical to many aspects of the decadal plan and should be immediately prioritized.

The second effort in this area identifies the need for increased and immediate investments in social and human behavioral sciences research, in order to address service gaps, especially for historically underserved and socially vulnerable populations. Investments in this area are absolutely necessary to ensure the full value and benefit from the weather information pipeline are achieved, including across the full diversity of decision makers and weather information users. A critical need is in the collection of relevant data that allow us to understand the needs and circumstances of our wide and varied populations across the nation.

A final key research effort that requires immediate prioritization is data assimilation. This is necessary to deliver sustained improvements in forecast skill and to train the next generation of experts in this area to fill an existing critical workforce gap. Investments in new observing systems cannot be prioritized if a commensurate data assimilation capability to leverage the observations within the modeling system does not exist. Without doubt, the effective utilization of existing and future observations depends on rapid and significant advancement in data assimilation capabilities.

INFRASTRUCTURE: Investments in infrastructure are clearly critical to our success and this second area involves three specific recommendations. The first is that NOAA must accelerate and enhance the ability to deliver to all stakeholders the full volume of foundational data that is generated across their many Centers. There is an exponentially increasing amount of data collected from radar, temperature and wind sensors, and satellites, as well as growing output from NOAA's suite of numerical models and access to these data is critical to many stakeholders within the weather industry. In many ways, NOAA/NWS has been a victim of its own success with the accelerating demand exceeding expectations. NOAA/NWS must commit to improved weather data dissemination, increased open science approaches, and expanded applications through weather industry partnerships. These data are the lifeblood of much our private weather industry, and full and highly reliable access to them is essential.

The second effort in this area involves high performance computing (HPC), which is likely the lynchpin of the success of weather research over this next decade. Without significant and sustained HPC resources, many of the core programs and efforts identified within the PWR report will not be possible. As such the report calls for an increase in capacity by two orders of magnitude (over the next ten years) with a 3:1 ratio of research-committed HPC to production-committed HPC. The benefits of accelerated and long-term investments into HPC cannot be overstated, nor can the detrimental impact of continuing with sub-optimal, incremental, and irregular investments.

The final effort of the infrastructure section focuses on guiding investments across Earth system observing networks. In some cases, these are existing networks where additional minimal investments could quickly enable more extensive use of the data. In others they are large investments that require committed strategic programs to be successful. I discussed earlier the tremendous value we have gained through the WSR-88D network that was installed primarily in the 1990s, yet that network is, at this point, primarily being sustained through multiple life system extensions, and only slow progress is being made toward a next-generation phased array network. A strong commitment for this next generation system is critical. Finally, the private sector is increasingly capable of partnering with, and or, delivering, new and innovative observing systems that can be both sold for commercial viability and shared with the NOAA/NWS. These opportunities must be actively identified and evaluated to identify the best and optimal path forward.

ACTIONS & IMPACTS: Specific to actions and impacts, one area that the report calls out repeatedly is reanalysis and reforecasting (RA/RF). These efforts are vital to Earth system model evaluation and improvement, to characterize extremes, and to provide training datasets for artificial intelligence applications. Unfortunately, NOAA does not have a good track record of prioritizing and investing in the generation of RA/RF. Ideally, they will become part of the operational production system, which will enable constant assessment.

As our country faces increasing climate and weather threats, an area of research that will likely bring significant benefit is to target the understanding and prediction of high-impact weather (HIW). Sharply focused research program on specific hazards (e.g., severe convection and tornadoes, hurricanes, fire weather, drought, and floods) will be the best and most expedient way to match the urgent need imposed by climate trends, population and infrastructure increases, and disproportionate impacts on vulnerable communities. These challenges are only going to grow further and early focused attention on providing relevant targeted observations, modeling, and forecasts, will best serve the WRN strategy.

The forecasting of water, both too little and too much, is one of the grand challenges of the weather forecasting industry. Water cycle extremes, i.e., drought and flood are leading causes of economic and human disruption, yet the prediction of precipitation extremes has been exceedingly slow to improve, with serious adverse impacts on people and the economy. Numerous opportunities exist that would increase resilience to extremes if precipitation, streamflow, and flooding could be better predicted. Immediate and substantial action to implement these recommendations are poised to yield high-value benefits in hazard mitigation and cost avoidance and economic efficiency and opportunity, and environmental justice.

NOAA PRIORITIZATION & INVESTMENT: NOAA and other partner Federal agencies deserve considerable praise for their long-term track record in the area of weather and climate forecasting. Nonetheless, there is little doubt that more could have been achieved and efforts must be made to strive for the best and optimal weather research trajectory possible; especially in the light of what will hopefully be significantly increased resources.

NOAA must focus on developing improved, increasingly objective, methods to balance investments across the weather information value chain and expand efforts to more precisely

target future investments. These plans should include ongoing prioritizations, carefully vetted implementation plans, and detailed gap analyses that are designed to call attention to any potential negative impacts. It is also critical that NOAA immediately develop more systematic methods to prioritize investments, including improved metrics to measure success, set goals, and focus resources. Not only will these methods better inform NOAA leadership, but they will also provide Congress with additional tools to prioritize investments for their greatest impact. Ideally these methods will be structured, will cross line offices, and will promote an integrated approach to budget decisions. They must also incorporate the broader weather enterprise. We have learned from the past that a thriving private industry can provide data, products, and services to federal agencies, which will help accelerate applied research and innovation through partnerships, including the academic sector.

The immediate first-step topics from the PWR report are, indeed, an excellent place for you to either accelerate and/or begin investing in immediately. If resources can be acquired to execute ~~on~~ the PWR plan, the benefits will be transformational as we move into this next decade. Having said that, the work will not be easy and will require the continued growth of the weather enterprise through increased collaboration and investment. The synergy will be high across the Enterprise, with NOAA focusing on its core mission, and private industry playing an increasingly essential role in the process.

I hope I have provided through this testimony some helpful insights that will support as you work to chart a course forward that will build off of our past successes, learn from past challenges, and build toward a better prepared and Weather Ready Nation.

I look forward to your questions. Respectfully, Dr. Brad Colman

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Short Bio – BRAD COLMAN

Bradley R. "Brad" Colman is the Director of Weather Strategy for Bayer/ Climate LLC, and President-Elect of the American Meteorological Society. At Bayer, he coordinates across multiple divisions to set weather priorities and works with scientists, engineers, and vendors, to deliver critical environmental information across Bayer's global agricultural industry.

Prior to joining the private sector, Colman enjoyed a long and diverse career with NOAA where he was both Meteorologist in Charge and Science and Operations Officer at the National Weather Service forecast office in Seattle, Washington; and a Forecaster in Juneau, Alaska. He also served as Acting Director of NOAA's Meteorological Development Laboratory, Silver Spring, Maryland; and worked as a Research Meteorologist at NOAA's Environmental Research Laboratory in Boulder, Colorado.

Brad is a member of the National Academy of Sciences' Board on Atmospheric Sciences and Climate (BASC); an elected Member of the Washington State Academy of Sciences; Co-Chair of the Environmental Information Services Working Group (NOAA-SAB); and a Bayer Science Fellow. Colman earned his Sc.D. in Atmospheric Sciences from the Massachusetts Institute of Technology (1984) and a B.S. in Earth Sciences from Montana State University (1977).

Chairwoman SHERRILL. Thank you, Dr. Colman.
I now recognize Dr. Carr for five minutes.

TESTIMONY OF DR. FRED CARR, PROFESSOR EMERITUS, SCHOOL OF METEOROLOGY, UNIVERSITY OF OKLAHOMA

Dr. CARR. Thank you. Good morning. Chairwoman Sherrill, Ranking Member Bice, Science Committee Ranking Member Lucas, Subcommittee Members, it is an honor for me to testify about the future of weather research and forecasting for our Nation. My name is Frederick Carr from the University of Oklahoma, and I speak to you today as one who has spent over 40 years either working to improve computer-based weather prediction models or advising NOAA leaders on how to improve U.S. weather prediction capabilities.

While National Weather Service forecasts are of high quality and provide great economic value, these forecasts are not world-best. Other global weather modeling centers produce greater forecast accuracy than we do. This gap shows that improved forecasts are possible and thus represents an opportunity for NOAA to serve the Nation even better than it does now.

How do we achieve this improved skill? The good news is that we can improve forecasts of all high-impact weather phenomena—hurricanes, wildfires, flash flooding, severe storms, tornadoes, blizzards, heat and cold waves, droughts—by investments in three things: A, increased observations of the Earth system; B, development of Earth system models; and C, high-performance computing. Investments balanced across all three areas will enhance the skill of future forecast models, improve the guidance provided to weather forecasters, and lead to greater public safety and protection of the Nation's infrastructure.

Let's expand upon the needed investments, A, observations. First, we need to maximize use of underutilized observations to realize the benefits of investments already made. Second, we need to add observational capacity to increase the detail and accuracy of Earth system measurements. For B, Earth system model, an Earth system model is a sophisticated forecast system that includes not only the atmosphere but the ocean, land surface, ice, air pollution, et cetera. The Earth system model is projected forward in time by supercomputers to produce weather forecasts and seasonal outlooks. Thus, we advocate that current models need to upgrade to Earth system models to enable more accurate forecasts on all timescales.

Here are some of the investments needed here. One, accelerate development of Earth system models by supporting research on the physical interactions among all its various components.

Two, use of Earth system models cannot be done without first determining the biases and errors in these models. This process must be done for all forecast systems.

Three, develop improved storm scale models to forecast hurricanes, severe thunderstorms, tornadoes, wildfire evolution, and storm surge.

And four, continue to invest in the Earth Prediction Innovation Center, or EPIC, to incentivize and support external partners to conduct research to improve NOAA's weather forecast systems.

And C, high-performance computing. None of the increases in weather forecast skill over the past 50 years would have been possible without high-performance computing, or HPC. The weather community thanks Congress for recent HPC allocations, but there are still three problems. One, the allocations are often done via supplements and not via a sustained annual investment.

Two, research HPC capacity lags operational HPC, whereas it should be at least three times greater.

And three, U.S. HPC is still behind other global weather prediction centers. Thus, the following investments are needed in this area:

One, expand HPC capacity by two orders of magnitude or 100 times over the next 10 years.

Two, concomitant investments in storage, transmission, access, security, and software engineering must also be made.

And three, NOAA must prepare for future HPC architectures, develop a culture of rapid adaptation, and train a skilled work force.

Finally, I note that six Department of Energy labs have already acquired or soon will acquire exascale computing systems, each of which is 25 to 50 times more powerful than all of NOAA's computer systems combined. Why can't NOAA get some of this exascale action? Thus, we encourage Congress and NOAA to be more ambitious in enhancing HPC capacity in order to better serve the American public. Thank you.

[The prepared statement of Dr. Carr follows:]

Written Testimony of Dr. Frederick H. Carr

Submitted to the Subcommittee on Environment
Committee on Science, Space, & Technology
U.S. House of Representatives

for the Legislative Hearing on
"What's the Forecast: A Look at the Future of Weather Research"

Tuesday, June 14, 2022, 10:00 am EDT
Room 2318 Rayburn House Office Building

Congresswoman Sherrill, Ranking Member Bice, members of the Subcommittee, it is an honor for me to testify about the future of weather research and forecasting for our nation. I thank the committee for their long-standing commitment toward improving the nation's forecasting services.

My name is Frederick Carr, and I am the McCasland Foundation Presidential Professor of Meteorology Emeritus in the School of Meteorology at the University of Oklahoma. I base this testimony on my 30-year experience either working to improve NOAA computer-based weather prediction models, or advising NOAA and National Weather Service leaders on how to improve U.S. weather prediction capabilities. I was also a Task Team Co-Leader on the NOAA Science Advisory Board report on the *Priorities for Weather Research*, and thus helped write many of its sections. The views that I am sharing today are my own, and not those of OU or NOAA.

This written testimony will concentrate on the research and actions needed to improve the **source** of public and private weather forecasts delivered to the public - the **complex computer models** developed and used by NOAA laboratories and the National Weather Service. These models, fed by millions of observations per day, generate forecasts of future weather on all spatial scales for time periods of minutes to seasons. The skill of these models determines the quality of the weather information provided to American citizens.

The weather forecasts produced by the NWS over the years have saved thousands of lives and provided billions of dollars in economic benefits. However, the United States does not currently have the best possible weather forecast capabilities, in part because its numerical weather modeling portfolio does not represent the best that science can achieve. For example, verification of global model forecasts (see Figure 1 below) shows that while weather forecast skill has improved over the past 45 years, the skill of the computer model NOAA uses to produce forecast guidance (Global Forecast System (GFS)) lags the models of two to three other international forecast centers. This indicates that not only are we under-serving the American public but also that the United States has the potential to provide more accurate and reliable weather information.

That is, **this gap represents an opportunity for NOAA** - that improved forecasts are possible - and thus we have the potential to serve the nation even better than we do now The public benefits of NOAA regaining a leadership role would be increased forecast accuracy, longer lead times, and finer-scale detail for severe weather, flooding and hurricanes - leading to greater public safety and protection of the nation's infrastructure.

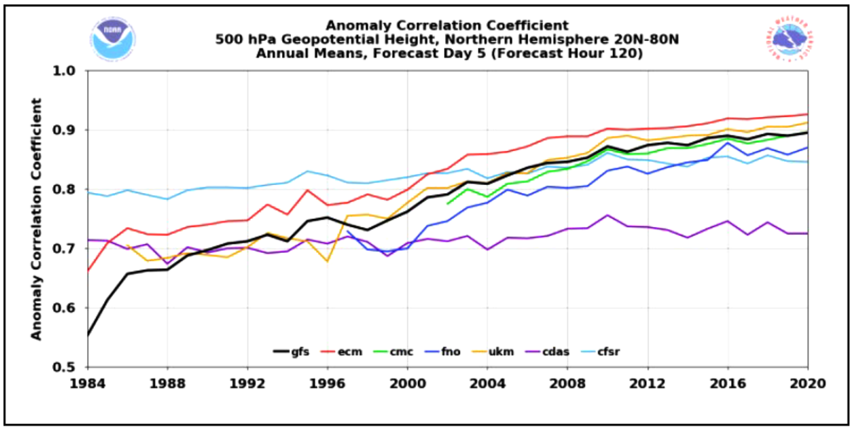

Figure 1: Five-day Forecast Skill of Global Models. gfs: *U.S. Global Forecast System (GFS);* ***ecm:*** *European Centre for Medium-Range Weather Forecasts (ECMWF);* ***cmc:*** *Canadian Meteorological Center;* ***fno:*** *Fleet Numerical (Navy);* ***ukm:*** *United Kingdom Meteorological Office;* ***cdas:*** *GFS used for National Centers for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR) Reanalysis;* ***cfsr:*** *GFS used for Climate Forecast System Reanalysis*[ix]

The research and actions needed for the United States to gain global leadership in weather prediction are well known. However, there is no simple "silver bullet" solution - major and **balanced investments are needed in several areas**:

How do we achieve this improved skill?

The good news is that we don't need to have separate approaches for each type of high-impact or hazardous weather phenomena that affect the U.S; - that improved forecasts of hurricanes, wildfires, flash flooding, severe storms and tornadoes, blizzards, heat and cold waves, droughts, etc. can all be addressed by the same set of investments in NOAA - investments in the three-legged foundational stool of:

(A) **Observations** of the earth system and their **assimilation** into the forecast models;

(B) Sophisticated weather forecast models (**Earth System Models**) that incorporate the physical processes governing the atmosphere and other earth components that affect it – ocean, ice, land surface, aerosols (pollution), etc.; and

(C) **High performance computing** (HPC) sufficiently powerful to enable the forecasts to be completed and disseminated in a timely manner.

The following discussion will outline what is needed in these three areas. Much of the material comes directly from the *Priorities for Weather Research* report (see Reference at end).

A. <u>Observations and Data Assimilation</u>:

The broad category of observations includes maximizing the use of existing data sets for additional value; filling critical observation gaps by adding to existing networks or establishing new networks that utilize advanced technologies; and supporting research and training in advanced data assimilation methodologies that are not being supported by other research agencies. The term "**data assimilation**" refers to methods for maximizing the information content contained in observations from diverse observing platforms (satellite, radar, aircraft, balloons, etc.) for the purpose of creating an accurate description of the current state of the atmosphere. This 3D "map" of the atmosphere can be used for situational awareness (e.g. – for warnings) or to provide the initial state for the forecast models.

Specific recommendations in this category include, along with their benefits:

1. **Maximize the use and assimilation of underutilized surface-based, airborne and marine observations** - *to ensure maximum value is derived from the full suite of observations made by the public, private and academic sectors*

2. **Maximize the use and assimilation of underutilized satellite observations** - *to ensure maximum value is derived from the full suite of satellite constellations and their many instruments in order to completely describe the global Earth system*

3. **Invest in new observational capacity** to increase the detail and accuracy of earth system measurements. The more observations we have, the better we can define the current state of the system – which leads to improved forecasts. Examples of actions needed to obtain important new observing systems include:

    a. **Develop and deploy a national high-resolution boundary layer, soil moisture and aerosol observing system** - *to improve understanding and forecasts of the layer where people live.*

b. **Increase observations of the ocean, its surface boundary layer, and of ocean-atmosphere feedbacks** - *to fully utilize knowledge of the ocean as a source of predictability in an Earth system model.*
c. **Develop a new phased-array radar network**, with additional **gap-filling radars** in areas not currently well-served - *to better detect significant precipitation and severe weather over a greater area and more equitably across the population*
d. **Prioritize smallsat/cubesat observation platforms** - to provide more complete and economical observations from space and *identify the role of smallsat/cubesat technologies for complementing large satellite systems.*

4. Prioritize immediate investments in fundamental **research on data assimilation** - *to deliver sustained improvements in forecast skill and to train the next generation of experts in this area to fill an existing critical workforce gap.*

5. **Advance coupled Earth system model data assimilation** for sub-seasonal to seasonal weather and water forecasting - *to enable observations in one Earth system component to influence all the other components.*

Note that these recommendations involve both investments in new technologies and workforce. The PWR report, e.g., suggests that one way to develop new expertise in data assimilation and increase workforce at the same time is to support the formation of a **university research consortium on data assimilation** together with the private sector and NOAA.

The positive outcomes of investing to increase observational capacity, data assimilation and the necessary skilled workforce can be summarized in this list:

- **Existing observations are more fully used in weather and water forecast models**, leveraging major current investments in observations to improve forecasts. The integration and collaboration with existing private sector weather observations, community scientists, and academia provides greater access to new data and higher resolution observations.

- Advances in data assimilation methods and tools **power better use of existing and new observations** to improve predictions from minutes to 2 years lead times.

- **More accurate and complete representation of the three dimensional state of the atmosphere and coupled Earth system components** (ocean, soil, rivers, snow) empowers advances in science and improves predictions of major storms and all weather conditions.

- A **highly technical workforce** is available to support the Nation's needs for state-of-the-art observations and data assimilation that underlies modern weather forecasting.

- A **national boundary layer, soil moisture and wildfire smoke observing network** fills a major observation gap over land, and enables improved predictions of storms, streamflow, air quality and smoke movement over hours, days, weeks and seasons.
- **Ocean observations**, including the mixed layer below the surface, revolutionizes storm and S2S forecasting by knowing how much ocean heat is available to fuel them.
- **Improved prediction of landfalling atmospheric rivers** provides a breakthrough in extreme precipitation forecasting from hours to two weeks, enabling more flexible reservoir operations that increases water supply reliability and reduces flooding.
- **A hybrid weather radar system optimized to regional needs** improves detection and warnings of severe storms and flash floods, and would quickly begin operation while the larger NextGen radars are developed, and continue as a hybrid weather radar network after that.
- Demonstrate that **a hybrid satellite observing system** capitalizing on smallsat/cubesat technology that incorporates a faster infusion of new technology **can cost-effectively serve NOAA's mission.** This supports NOAA's formal goal in its "Blue Book" to "Expand Commercial Space Activities."

B. Earth System Model

An Earth system model (ESM) is a **sophisticated weather forecast computer model** that includes all the important physical, chemical and biological processes that affect weather and climate. The relevant components include the atmosphere, oceans, land surface, cryosphere, biosphere and hydrologic and biogeochemical cycles, and the interactions (coupling) among them. The ESM is projected forward in time by supercomputers to produce weather forecasts and seasonal outlooks. Current models used only for weather prediction (such as the GFS) do not include as many processes as do ESMs, in order to complete their forecasts on time. However, recent research has shown, as we desire to increase forecast skill for longer periods (greater than 7-8 days), that these omitted processes are important to medium-range forecasts. Thus **we advocate that current weather models need to upgrade to ESMs** to enable more accurate one to two week forecasts as well as improved sub-seasonal to seasonal outlooks. This is what our international colleagues have done, and we need to do so as well.

Here are of the major investments needed to advance forecast skill:

1. **Accelerate development of Earth System Models** - by supporting research on the appropriate physical processes and interactions among its various components. These fully-coupled models are vital for improving the accuracy and extending the lead time for 1-2 week forecasts, to acquire skill in the 2-4 week period, and to increase skill in

seasonal outlooks for not only the atmosphere, but also for the oceans, river flows, ice behavior, and evolution of aerosols (smoke) and pollution.

2. Use of ESMs cannot be done without determining the biases and errors in the models, which can be found from a process called **reanalysis/reforecast**; this process, which is computationally demanding, **should be completed for all forecast models** used by NOAA. To accomplish this, establish a regular, sustained Earth system reforecasting activity - to enable a more effective cadence and accelerated process for operational model improvements.

3. **Support research on how to perform data assimilation for fully-coupled ESMs**. This problem is far from being solved, and must be addressed in order to maximize the benefits of including all vital earth system components.

4. Emphasize the **understanding and prediction of high-impact weather** (Figure 2) to match the urgent need imposed by climate trends, population and infrastructure increases, and disproportionate impacts on vulnerable communities. **Develop high-resolution (1 km or less) storm-resolving models** to forecast hurricanes, severe thunderstorms and tornadoes, wildfire evolution, storm surge, and other extreme events. These models should be nested within the foundational ESM and have additional physics to address their intended purpose.

Figure 2: Images of High Impact Weather. *Moving clockwise starting in upper left: 1) Lightning strikes Citibank Ballpark in Midland, Texas. Credit: Brian Curran, NWS. 2) "Snowzilla" that hit Northeastern US in January 2016. Credit: Joe Flood. 3) Hurricane Ike storm surge in September 2008. Credit: NOAA. 4) Drought in Texas in August 2013. Credit: Bob Nichols, USDA. 5) Supercell thunderstorm in Oklahoma in June 2008. Credit: Sean Waugh, NOAA/NSSL. 6) Wildfire. Credit: NOAA.*

5. Support the use of **new post-processing tools such as AI and machine learning** to improve the accuracy and reliability of the forecasts presented to the public. This requires that **all modeling systems consist of ensembles** (many forecasts generated from slightly different initial conditions), so that probabilistic forecasts can be produced.

6. In addition, **support is needed for the social sciences** to determine the best modes of communication of weather warnings and forecasts; that is, to learn how the public receives, interprets and responds to weather information, and what are the best ways to ensure prompt, safe and effective actions.

7. Continue to **invest in the Earth Prediction Innovation Center (EPIC)** to incentivize and support external partners to conduct modeling research and development in a manner that contributes to improvement of NOAA weather forecast systems

The **positive outcomes** of investing in improved Earth System Models and their many applications for high-impact weather and long-range forecasts include:

- **A seamless and fully coupled modeling framework** that provides a holistic treatment of key processes within, and interactions among, the components of the Earth system.

- **World best operational numerical weather prediction capability** that provides more accurate weather information to the American public, thus decreasing our vulnerability to weather extremes. This is in concert with the aspiration goal of the new Interagency Council on Advancing Meteorological Services (**ICAMS**) which states "the United States will lead the world in meteorological services via an Earth system approach, providing societal benefits with information spanning local weather to global climate."

- **Enhanced prediction of Earth's water cycle extremes** - to improve forecasting of floods, droughts and hydrologic processes at national to street-level distances and across all time scales to inform life-saving decisions.

- **Advanced hourly to seasonal prediction of fire weather, aerosols (smoke) and air quality** (pollution) that better inform the public during wildfire events and hazardous air pollution episodes.

- **Advanced knowledge of coastal processes** that improves coastal forecasts of waves, currents, storm surges, total water levels (inundation) and water quality that informs navigation and commercial shipping, alternative energy, pollutant tracking and cleanup, fisheries, recreation, and search and rescue.

- **Improved forecasts of high-impact weather** that provide more accurate and timely watches and warnings for extreme weather events. For example, the "Warn of Forecast" goal (see Box 1) of the NWS will be achieved.

Box 1: "Warn-on-Forecast"
As an example of a needed high-impact weather forecast capability, consider the warnings for tornadic thunderstorms, which today are based on observations. The NWS "Warn-on-Forecast" vision requires the rapid cycling of convection-resolving models producing a suite of ensemble forecasts that helps forecasters anticipate tornadoes before they form. However, this is not possible without enabling all aspects of the aforementioned three-legged foundational stool, specifically**: (a) increased radar, PBL and other observations and the assimilation of such observations; (b) improvements in high-resolution models and their ensembles; (c) major increases in computer power.** In addition, research is needed on how best to communicate actionable information to all impacted residents. These investments would significantly increase the lead time for tornado warnings, thus saving lives and enabling resource protection. Similar investments in other HIW forecast needs will also increase warning lead times for flash flooding, wildfire spread, hurricane intensity, storm surges, major ice storms, etc., permitting earlier evacuations and other protective actions, again saving lives and property.

C. High Performance Computing

None of the increases in weather forecast skill over the past 50 years would have been possible without acquisition of more and more powerful mainframe computers - or high performance computing (HPC – see Box 2). **Improvements in weather forecasts are directly limited by the availability of sufficient computing resources to develop, test and operate next-generation forecasting technologies.** The weather community thanks Congress for recent allocations for increased computing, but there are three problems**: (1) The allocations are frequently done via Supplements, and not via sustained annual investments; (2) The operational HPC has been increasing faster than that for research; and (3) the U.S. is still behind other global weather prediction centers.** Thus we encourage NOAA, given the urgency of the need to provide better weather and climate information to the American public, to be more proactive and farsighted in its high performance computing (HPC) strategies.

Box 2: High Performance Computing
High-performance computing (HPC) generally refers to aggregating computer power to achieve computational or throughput rates that are much higher than are available on a laptop or desktop computer for the purpose of solving large, complex quantitative problems. HPC implies extraordinary computational speed and transport of data into, out of, and within the system, and rapid storage and retrieval of associated high volumes of data. HPC systems include high-speed networks connecting to

disk systems or cloud-based solutions for both real-time and archival storage, and facilities that enable the rapid processing, analysis and visualization of data. All these components have to scale in size, complexity, capacity, and speed in proportion to the computational elements.

Some of the factors that drive the massive HPC requirements of weather forecasting include the need for higher resolution of models, enormous increases in data (especially from satellites), advanced data assimilation complexity, ensemble forecasts (usually 50-100 are needed), the new Warn-on-Forecast system, new sub-seasonal and seasonal forecasts, reforecasts and reanalyses for all modeling systems, AI applications, and the NOAA and community research needed to catalyze scientific discovery and improvements in these topics. Despite recent investments, the United States still substantially lags other countries in its investment in computing to support both weather-related research and forecasting. For example, included in the United Kingdom Meteorological Office's recent $1.6 billion contract with Microsoft is a six-fold increase in computing power over their current system, in contrast to the three-fold increase the new WCOSS2 system provides to NCEP.

While producing the *Priorities for Weather Research* report, we learned that all NOAA labs and centers felt **handicapped by the lack of availability of greater compute resources**.

Thus a comprehensive plan for the HPC needed to support both the research and operational weather demands of NOAA and its community partners over the next ten years should be developed. Further, the consensus of the weather community is that allocations for research and development should outweigh operational allocations by several times, and certainly be higher than the current 2:3 research to operations ratio in NOAA. (This ratio is determined from NOAA's HPC chart that shows, by mid-2022, two 12 peta floating point operations per second (PF) systems for NCEP in Arizona and Florida (24 PF) and 16 PF for all NOAA research HPC systems for a total of 40 PF.) **We advocate for at least a 3 to 1 research vs operations ratio, noting that both need to increase.**

An estimate of future HPC needs should be both demand-based and reasonable. From an operational NWP perspective, a four-fold increase in model resolution in the next ten years (sufficient for convection-permitting global NWP and kilometer-scale regional NWP) requires on the order of 100 times the current operational computing capacity. Such an increase would imply NOAA needs a 3-4000 PF of operational computing by 2031. Exascale (1000 PF) computing systems are already being installed at several Department of Energy (DoE) laboratories and it is likely that each of these national labs will have 50-100 EF by 2031. Because HPC resources are essential to achieving the outcomes discussed in this testimony, **it is reasonable for NOAA to aspire to a few percent of the computing capacity of these DoE labs** at a minimum. If, e.g., operational HPC increases to 3 EF by 2031, NOAA (and its partners) will need around 9 EF of weather R&D computing by 2031, in order to achieve a 3:1 ratio of research to operational HPC.

As HPC system components scale up, both systems software and applications software need to evolve or sometimes be radically overhauled to keep pace, which requires sustained investments in software engineering. Thus **workforce and training investments are also needed**.

High performance computing is undergoing a rapid transformation with the emergence of cloud-based computing capabilities, new computing architectures such as graphics processing units (GPU), massively parallel exascale systems, and quantum computers. **NOAA is insufficiently prepared to leverage these new computing technologies** from both an application and modeling, and workforce perspective, and as a result, will be inhibited in its ability to advance weather forecasting in the coming decades unless it becomes a more proactive and not reactive, adopter of new computing technologies.

The bandwidth available on wide-area networks is increasing more slowly than the throughput capabilities of HPC computational systems, so it is becoming increasingly important that data storage, processing, analysis and visualization systems are **co-located with the HPC computational elements** in order to minimize the long-haul transport and redundant replication of high-volume data sets.

A substantial portion of NOAA's HPC investments historically have come by way of special *ad hoc* appropriations from Congress. The lack of long-term (decadal) and sustained Congressional commitments to advance NOAA's computing portfolio inhibits NOAA's ability to be more proactive in developing next-generation HPC strategies, expertise and applications.

Thus the following investments are needed:

1. **Expand HPC capacity by two orders of magnitude (100X) over the next ten years** to support operational forecasts and NOAA modeling research. HPC must be an immediate and ongoing investment. Without sufficient HPC investments, the loss of potential advancements is tremendous and cannot be overstated.

2. **Research HPC in NOAA should be at least three times the operational HPC capacity**.

3. Concomitant **investments in storage, transmission, access, security and software engineering workforce** must be made as HPC capacity increases.

4. A **sustained increased annual appropriation for HPC should be part of NOAA's budget**, to facilitate planning and the ability to reach our recommended HPC goal.

5. While most of these resources should be acquired and managed by NOAA, a major portion of the resources **should be dedicated to NOAA's partners in academia, other government institutions, and the private sector** to support research and development of NOAA's weather forecasting portfolio such as the Unified Forecasting System. This will require weather enterprise access to lower security HPC assets that are not constrained by the expense and security requirements of operational assets.

6. NOAA must immediately invest in long-term programs to leverage new and emerging high performance computing architectures such as cloud, GPUs, exascale and quantum, in order to keep pace with technological advances and develop the software tools and IT workforce for the future. That is, **NOAA should adopt a culture of rapid adaptation of evolving computing technologies** and not latently react to these changes, as well as develop a workforce skilled in these new technologies. This will enable NOAA to achieve higher compute-per-dollar, and compute-per-watt efficiencies with its computing resources, resulting in higher technical efficacy and a lower carbon footprint.

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Dr. Fred Carr Biosketch

Dr. Fred Carr is currently the McCasland Foundation Presidential Professor Emeritus and Director Emeritus in the School of Meteorology at the University of Oklahoma. After receiving his PhD from Florida State University under Dr. T. N. Krishnamurti, and having a post-doc position at SUNY-Albany with Dr. Lance Bosart, he began his 43-year career at OU in 1979. His research interests include numerical weather prediction, data assimilation, synoptic, mesoscale and tropical meteorology, and use of new observing systems. Dr. Carr has provided service to a wide variety of professional activities, including the National Research Council's "Network of Networks" report, the Oklahoma Mesonet Steering Committee, the UCAR Board of Trustees, Associate Director of the NSF Center for the Analysis and Prediction of Storms and as a founder of COMET at UCAR. He was Director of the OU School of Meteorology for 14 years, during the period when the National Weather Center was built. He has served as Co-Chair of three committees (UCACN, UMAC and CMrC) that provided guidance to NCEP, NWS and NOAA on improving U.S. Numerical Weather Prediction, and is now co-Chair of NOAA's Community Modeling Board. He was President of the American Meteorological Society in 2016 and served on the AMS Executive Committee from 2015-2019. He is a Fellow of the AMS and currently chairs its Committee on Ethics.

Chairwoman SHERRILL. Thank you, Dr. Carr. Next, I recognize Dr. Petty for five minutes.

TESTIMONY OF DR. KEVIN R. PETTY, VP, WEATHER AND EARTH INTELLIGENCE, SPIRE GLOBAL, INC.

Dr. PETTY. Chairwoman Sherrill, Ranking Member Bice, and Ranking Member Lucas, as well as the rest of the Members of the Subcommittee on Environment, thank you for allowing me the opportunity to speak with you about what is a very important topic for our Nation, priorities for weather research and forecasting.

As part of my comments, I would like to share some high-level thoughts and perspectives on the Priorities for Weather Research report. I would also like to highlight the role of the private sector in achieving the desired outcomes of the report.

However, first, I would like to convey why this topic is so important to me. I have essentially spent my entire career working in the weather enterprise. I have held positions in the public, private, and academic sectors. During this time, I've endeavored to promote and contribute to research and development efforts that result in significant improvements in weather analysis and forecasting.

However, on December 30, 2021, this endeavor became quite personal. On that day, Colorado saw its most destructive wildfire in history, the Marshall Fire. The Marshall Fire, which was exacerbated by high winds and dry conditions, burned roughly 6,000 acres, destroyed over 1,000 homes and structures, and damaged nearly another 180, one of which was my home. We watched as entire neighborhoods burned to the ground in minutes. And to this day, my family remains displaced. Although we have made great strides in weather research and forecasting over the last several decades, there is still much to be done if we're going to prevent billion-dollar disasters such as this one.

The Priorities for Weather Research report is a timely exemplary document that identifies and recommends investments designed to foster new and improved capabilities that can serve to reduce the number and severity of high-impact events such as the Marshall Fire. The report rightly expresses the fact that the scope of the investments necessary to support the advancement of weather for society is vast. Thus, it will be difficult for NOAA to make the material investments across all of the identified priority areas. Where it makes sense, NOAA should attempt to partner not only with the academic sector, but it should also make use of the competencies and resources found in the private sector. As the private sector has grown, so has its ability to carry out rigorous, high-quality research and development.

For example, Spire made significant investments that led to the successful deployment of one of the world's largest multipurpose satellite constellations with over 100 satellites operationally in orbit today. This constellation delivers a rich and unique set of data about the atmosphere and Earth. Spire is proud to be a Weather-Ready Nation Ambassador, and it's honored to be a supplier of radio occultation data to NOAA through the Commercial Data Program. None of this would have been possible without Spire's willingness to invest in science and technology research.

NOAA is and will remain a cornerstone of the weather enterprise. It serves as a catalyst in driving research and forecast investments to mitigate the impacts of weather, water, and climate extremes. It is crucial that NOAA's investments are strategic, particularly from the perspective of ensuring that our Nation is a global leader in weather prediction. Fundamentally, it is forecast accuracy and reliability that drive the effectiveness of downstream weather-related products, services, and solutions, including many offerings found in the private sector. NOAA should recognize and carefully consider its limitations and formulate a research and development investment strategy that includes clear tradeoffs.

As part of its efforts, NOAA would benefit from identifying and acknowledging the investments and contributions being made by others in the weather enterprise. It should not run the risk of replicating such investments, nor should it risk diluting its investments to the point that tangible and sustained progress in key areas is limited or negated, especially for core areas associated with forecast accuracy and reliability. This will require strong leadership and an organizational culture that embraces a more well-defined and focused approach.

Most importantly, NOAA's ability to effectively respond to the recommendations found in the report is rooted in its ability to create strong, long-lasting partnerships. By doing so, our great Nation will be able to recognize the full power and extent of the weather enterprise and what it has to offer.

Thank you for this opportunity to share this testimony. I hope you found it helpful. And I welcome any questions or comments you may have.

[The prepared statement of Dr. Petty follows:]

Testimony of Dr. Kevin R. Petty, Vice President of Weather and Earth Intelligence, Spire Global Inc.

What's the Forecast: A Look at the Future of Weather Research

Submitted to the

Subcommittee on Environment

Committee on Science, Space and Technology

United States House of Representatives

14 June 2022

Chairwoman Sherrill and Ranking Member Bice, as well as the rest of the members of the Subcommittee on Environment, thank you for allowing me the opportunity to speak with you about what is a very important topic for our nation – priorities for weather research and forecasting.

My name is Kevin Petty, and I am the Vice President of Weather and Earth Intelligence at Spire Global Inc. Spire is a leading global provider of space-based data, analytics, and space services. We offer unique Earth system-related datasets and insights that help to facilitate enhanced operations across a number of industries.

As part of my comments, I would like to share some thoughts and perspectives on the NOAA Science Advisory Board's (SAB)'s Priorities for Weather Research (PWR) report. I would also like to comment on the role of the private sector in achieving the outcomes of the report. First, let me begin by sharing some additional background information on Spire and how it fits into today's discussion.

Spire was founded in 2012, and in August of 2021 the company went public on the New York Stock Exchange. During the last 10 years, Spire has launched over 150 satellites. It now operates one of the world's largest multipurpose satellite constellations, with over 100 satellites operationally in-orbit today. The constellation is predominantly built around Spire's 3U CubeSat platform called the Low Earth Multi-Use Receiver, or LEMUR. However, Spire is expanding its portfolio to include larger, more powerful 6U, 12U, and 16U form factor satellites. In addition to launching its own satellite constellation, Spire has an established Space Services division that is dedicated to deploying end user applications and sensors into space quickly, reliably, and efficiently, allowing for cost-effective, fast roll-out of new, novel capabilities.

Spire's constellation facilitates a number of data-related solutions. The company has become the global leader in capturing, analyzing, and distributing reliable, high quality Automatic Identification System (AIS) data, which is associated with maritime vessel tracking. Such data and information help to foster improved asset management, supply chain efficiency, and safety. Similarly, Spire's collection of Automatic Dependent Surveillance-Broadcast (ADS-B) data enables accurate, reliable global flight tracking, including over the oceans and remote regions of the Earth, allowing airline, aircraft, and airport operators to optimize across their network, better understand aircraft utilization, and predict maintenance windows.

Most pertinent to the discussion today is the fact that Spire's low earth orbiting satellite constellation uses radio frequency sensors to constantly gather a rich and unique set of data about the atmosphere and the Earth's surface. Through its satellite constellation, Spire collects the highest volume of Global Navigation Satellite Systems Radio Occultation (GNSS-RO) profiles in the world. The GNSS-RO technique, which analyzes the propagation of GNSS radio signals through the Earth's atmosphere, is used to produce data about the vertical structure of the atmosphere, including temperature, water vapor, and pressure. NOAA and other national meteorological centers are using these data to improve weather prediction by assimilating the data into numerical modeling frameworks. Furthermore, Spire is using its own RO data, along with numerical weather prediction and artificial intelligence/machine learning, to deliver targeted

weather-related solutions to its customers in the business-to-business domain (e.g., Maritime, Aviation, Energy, Agriculture, etc.). It is also worth noting that ionospheric data, such as Total Electron Content (TEC) and scintillation, are gathered during the process of generating RO profiles. These data can be used to analyze and better predict space weather and its impacts on communication systems and power grid operations.

Spire's technology also supports the acquisition of unique environmental datasets worldwide such as soil moisture, sea ice extent, altimetry and other Earth properties. This is accomplished through the use of GNSS-Reflectometry. By leveraging these data to fuel research and development, innovative solutions can be created to address a number of disparate issues ranging from future food production to evolving shipping routes to changes in land use.

Spire is a prime example of how the Weather Enterprise continues to undergo significant transformation, particularly from the standpoint of private sector innovation and growth. This transformation began in large part in the mid-1990s and has accelerated since that time. Private sector growth has been accompanied by an expanding set of novel offerings and capabilities. Like Spire, several companies are delivering products and services to their customers by running numerical weather prediction models in-house and conducting research to advance modeling frameworks, including data assimilation. This was unheard of a few decades ago. For many years, weather-related companies were limited to selling terrestrial-based hydro-meteorological equipment, largely to the public sector. More recently, there has been private-sector expansion in the development and launch of space-based platforms for the advancement of weather analysis and forecasting. New business models have also arisen around the ownership and operation of equipment and infrastructure, with a focus on selling data instead of selling sensors. The translation of data into insights that support critical decision-making continues to be a central theme of many private sector offerings in the Weather Enterprise. In fact, sizable investments are being made in the creation of impact-based solutions rooted in artificial intelligence and machine learning techniques. Finally, the private sector is working to build and enhance pathways for efficient, effective distribution of data and information to end users, targeting user-tailored products and services. This includes the development of Application Programming Interfaces (APIs), web and mobile applications, infotainment system plug-ins, and plug-ins for smart devices. The aforementioned changes and progress in the private sector have generated a stronger, more diverse Weather Enterprise, with the capacity to tackle some of the nation's most challenging weather and climate issues. It is only by creating and leveraging strong partnerships will our great nation be able to recognize the full extent of the Weather Enterprise.

The Weather Enterprise has changed substantially over the last several decades. Specifically, the private sector has contributed significant innovation and experienced substantial growth. As a result, the influence and contributions of the private sector can be felt and experienced throughout the weather data and information value chain. Some companies in the Weather Enterprise have extensive expertise in specific parts of the value chain (e.g., observations, computing, and information delivery and translation). Accordingly, the private sector stands poised and is well-positioned to contribute to improvements spanning research to operations, including support of NOAA's mission.

The NOAA Science Advisory Board's Priorities for Weather Research report is a timely, exemplary document that identifies and recommends actions associated with weather research investment designed to culminate in new and improved capabilities that can serve to significantly enhance public safety and economic stability and resilience. The report calls out three essential pillars for investment – (1) Observations and Data Assimilation, (2) Forecasting, and (3) Information Delivery. One could argue that Observations and Data Assimilation are essentially two distinct pillars that should be addressed independently. Nonetheless, both are worthy of meaningful investment. Using the pillars as a foundation, the report proceeds to articulate some thirty-three recommendations, along with key findings. As expressed in the report, "The scope of investments necessary to support the overall advancement of weather for society is vast." As such, the human, material, and intellectual resources needed to achieve the desired outcomes are equally sizable.

Because the research and development (R&D) recommendations in the report span such a large array of priorities, it is clear that it will be difficult for NOAA to make material investments across all of the identified priority areas. Nevertheless, it is good to have a comprehensive picture of the research needs and requirements, since this will aid in formulating an effective investment strategy, including trade-offs. Where it makes sense, NOAA should not only partner with the academic sector, but it should also make use of the competencies and resources found in the private sector. Too often, the private sector is overlooked when the discussion turns to basic and applied research. However, as the private sector has grown, so has its ability to carry out R&D in all forms underscored in the SAB PWR report. This has been demonstrated by multiple private sector companies including Spire, Vaisala, IBM, Amazon, Ball, Campbell Scientific, and Advanced Environmental Monitoring, to name just a few.

In the case of Spire, significant company R&D investments were made, which led to the successful development and deployment of its Low Earth Orbiting (LEO) satellite constellation. In addition, these investments included signal processing research, which has advanced Spire's understanding as it relates to measuring and deriving Earth observations from space. Ultimately, Spire has been able to operationalize the collection of reliable, high-quality GNSS-Radio Occultation and GNSS-Reflectometry data to support its customers across all sectors. In fact, Spire is proud to be a Weather-Ready Nation Ambassador and honored to be a supplier of GNSS-RO data to NOAA through the Commercial Data Program (CDP). This would not have been possible without Spire's willingness to invest in science and technology research. Research is at the core of the company's success.

In 2017, the Weather Research and Forecasting Innovation Act was signed into law. This piece of legislation directed NOAA to explore the acquisition of commercial weather data. This legislation has helped to positively shift the data procurement paradigm for NOAA, with a focus on reducing the cost of ownership compared to conventional approaches. While the directive from the legislation, as well as NOAA's response, should be commended, the interaction in this paradigm remains transactional in nature. There is still room to enter into a stronger partnership model. Such a model could include working closely together from the ideation phase (e.g., new sensor), through the research phase, to development

and deployment, and into operations. This type of collaborative approach will aid in stimulating innovative solutions, reducing risks, and meeting end-user needs. Most importantly, it can build trust.

Weather-related research and development competencies in the private sector run deep in several companies in the Weather Enterprise. These competencies include space-based and terrestrial observing sensors and systems, data assimilation and numerical modelling, artificial intelligence and machine learning, and user experience. This generates opportunity for scientific partnership across all sectors of the Enterprise. However, in terms of public-private partnerships and NOAA's investment in weather research, it is imperative that investments be made in research ventures with companies that have previously demonstrated the ability to conduct rigorous, distinguished research, along with the capacity to transition research to operation. By doing so, R&D risks can be significant lowered.

The PWR report also emphasizes, "...the urgent need imposed by climate trends, population and infrastructure increases, and disproportionate impacts on vulnerable communities..." In order to address this urgency, there is a need to quickly adapt to these trends. This requires an acceleration in the pace of research, along with faster adoption and implementation of credible outcomes. One way to accomplish this is by embracing R&D strategies that are not limited by rigid, siloed, and bureaucratic practices. Due to market demands, private sector companies have incorporated Agile and Lean strategies and practices in an effort to foster faster, flexible, iterative, efficient R&D environments, with a focus on end-user value. An attempt is made to fully address the research to operations pathway. NOAA should consider wider adoption of Lean and Agile throughout the organization. Moreover, it may be possible for NOAA to benefit from the research and development frameworks established by some companies in the Weather Enterprise, especially as it relates to increasing the pace of R&D.

It is important to recognize that NOAA has indeed taken steps to cultivate research engagement across broad parts of the Weather Enterprise, with the goal of accelerating impactful research and innovation. For example, NOAA should be acknowledged and applauded for its efforts associated with the Earth Prediction Innovation Center (EPIC), which supports and incentivizes a broad spectrum of NWP researchers. Initiatives such as EPIC have the potential to deliver innovative results quickly by creating opportunities for contribution and collaboration across the weather community, regardless of where an NWP researcher may sit in the Enterprise. It is these types of investments and initiatives that will accelerate model improvements, helping NOAA to meet its goals and objectives.

Given the fact that there are so many research priorities, as demonstrated by the PWR report, it is crucial that NOAA's investments in weather research are strategic, particularly from the perspective of ensuring that our nation is the global leader in weather prediction. Fundamentally, it is forecast accuracy and reliability that drive the effectiveness of downstream weather-related products, services, and solutions. Furthermore, the capacity to share and disseminate data and information is a key to success. Thus, special attention should be given to those research investments that will result in material improvement in these areas. The PWR report does well to articulate some of the investment pillars that would help to address these issues.

- **Observational Gaps**: it is essential that investments be made to address observation gaps, especially in the boundary layer and in data-sparse regions. This should include a balance between terrestrial, airborne, and space-based sensors and platforms. NOAA should consider the most effective and feasible solutions to close observation gaps including, but not limited to:

  - Sensor/system acquisition, ownership, and operation
  - Data buys
  - Co-hosted sensor deployment and operation (e.g., satellites)
- **Computing infrastructure:** NOAA must obtain access to more computing resources. This should likely include a hybrid approach (e.g., on premise and off premise resources, cloud and HPC). Computing resources must effectively and efficiently facilitate research, operations, data storage, and data/information dissemination.
- **Data Assimilation and NWP:** Investment in an Earth system modeling approach is absolutely necessary. However, care must be taken that such investments do not result in a proliferation of data assimilation and modeling systems, although it is recognized that one system may not fit all needs.

NOAA is and will remain a cornerstone of the Weather Enterprise, and in its capacity, it should be careful not to become all things to all people. As part of its investment strategy over the next decade and beyond, NOAA should carefully consider and account for the investments being made by others in the Weather Enterprise. For example, there continues to be a considerable amount of investment from the private sector to address the needs and requirements of select industries such as agriculture, energy, aviation, maritime, insurance, as well as a host of others. These needs have centered on tailoring data and information in an effort to increase safety and operational efficiency. NOAA should not run the risk of replicating these types of investments. Nor should it risk diluting its investments in weather research and forecasting to the point that tangible and sustained progress in key areas is limited or even negated, especially for core areas associated with forecast accuracy and reliability. This will require strong leadership and a willingness to make concrete and definitive investment trade-offs. It may also require a cultural shift in NOAA that embraces a more well-defined and focused approach when it comes to investments in weather research and forecasting. Fundamentally, NOAA should refrain from attempting to invest in everything, and where it makes sense, NOAA should develop and invest in strategic partnerships with the academic community, private sector, and other organizations to attain its weather research and forecasting goals and objectives.

Thank you for the opportunity to present this testimony. I welcome any questions or comments that you may have. I can also provide additional information as needed.

Short Bio for Dr. Kevin R. Petty

Vice President of Weather and Earth Intelligence, Spire Global Inc.

Dr. Kevin Petty is the Vice President of Weather and Earth Intelligence at Spire. Spire is a leading global provider of space-based data, analytics, and space services. Dr. Petty oversees science and engineering associated with the delivery of weather-related products and solutions, as well as the development of new observations that support our understanding of the planet. In addition, he is responsible for helping to set the strategic direction for the Weather and Earth Observation business lines within Spire. As part of his role, he closely interacts with members of the national and global weather enterprise including, but not limited to, government agencies, academia, and other private-sector providers.

Before joining Spire, Dr. Petty was the Director of Science and Forecast Operations at The Weather Company, an IBM business. Prior to that, he served as the Chief Science Officer for Vaisala, a Finland-based company that develops meteorological instrumentation. He has also worked as a Project Scientist and Scientific Program Manager with the National Center for Atmospheric Research (NCAR) and as an accident investigator and Senior Meteorologist for the National Transportation Safety Board (NTSB). Dr. Petty graduated with an M.S. and Ph.D. in Atmospheric Sciences from Ohio State University and a B.S. in Mathematics/Secondary Education from Illinois College.

Chairwoman SHERRILL. Thank you, Dr. Petty.

So at this point, we will begin our first round of questions, and I recognize myself for five minutes.

Unfortunately, New Jersey is no stranger to catastrophic flooding events, as demonstrated recently by Hurricane Ida. However, large-scale events are not the only weather concern in my district. As I mentioned in my opening statement, the Northeast Regional Climate Center predicts that by the end of this century, precipitation will increase by as much as 50 percent. These changes in precipitation area flooding are already being felt by the residents in my district.

And I recently introduced the *PRECIP Act,* which passed in the House, and will direct NOAA to update out-of-date precipitation data that can be utilized for decisionmaking in extreme weather events such as hurricanes, as well as for more long-term decisions, such as buying a home in a flood zone. NOAA's Precipitation Grand Challenge aligns with this goal. Among other targets, it aims to update weather models to provide timely and accurate forecasts that can be utilized by citizens to make crucial decisions.

Dr. Colman, as a Member of NOAA's Science Advisory Board, you have experience with their weather modeling framework. How will investments into NOAA's weather research assist the agency in their work to update precipitation data and meet this grand challenge? What work do you needs to be done in collaborating with other members of the weather enterprise to ensure that this data meets end users in a timely and accessible way?

Dr. COLMAN. Thank you, Chairwoman Sherrill, for the question. It's a complicated answer in my mind. The return frequency of events and the shift in probabilities of events, as we move through this period of climate change, are difficult to measure and ultimately require a collaboration across many different entities and sectors. Certainly, as we move into the next generation of models, as Dr. Carr presented about Earth system modeling, one aspect is the reanalysis and reforecasting piece, which I mentioned and emphasized how critical it is to successfully develop these new models. This work will give us insights into the distribution of events and the evolution of events as we move forward. So investing in the model and associated infrastructure is primary, but it goes into statistical analyses as well, and how you do the analyses to attribute different events to different causes.

Yes, maybe I'll stop there.

Chairwoman SHERRILL. Well, thank you, Dr. Colman.

And, Dr. Glenn, as a New Jersey resident, you are familiar with the devastation that hurricanes like Sandy, and more recently, Ida caused New Jersey due to extreme precipitation. How would advancing research related to the total water level support improvements to weather forecasting overall? How would the updates to probable maximum precipitation and Atlas 14 estimates like what is included in *PRECIP*—in my *PRECIP* and the *FLOODS Act* relate to this work?

Dr. GLENN. Thank you, Chairwoman Sherrill. Total water level is the critical piece of this because we see with hurricanes and storms, they're traveling slower, there's more rain involved with them, with the warming ocean, there's more moisture in the atmos-

phere. And so improving all these models is one of the very important pieces of this. That improvement over and over again, you'll see through the PWR report, comes through several levels. One is the observations that are made there to improve our understanding of the processes. Precipitation is a very hard process to forecast. It's like hurricane intensity. These are the two important pieces that—the two critical pieces. How do we get the hurricane intensity right? How do we get the quantitative precipitation right? That's why there's those grand challenges.

So critical pieces of that, especially for a place like New Jersey, whereas we look at the climate projections and we see that storms are going to be more slower moving, there's going to be more heavy rainfall, there's going to be stronger winds. So the stronger winds will produce more storm surge, the heavier rains will produce more flooding from the rivers, and so the combination of New Jersey being in the middle of that, you know, ocean water coming from the ocean side, the river water coming from the other side, so it's a very important piece to get the total water level right. In Sandy, there was so much of this discussion to figure out how much was from the ocean and how much was from the rivers. Thank you.

Chairwoman SHERRILL. Thank you and I'll—very quickly because I just have a few minutes. A lot of States are undertaking their own research initiatives such as New Jersey's DEP (Department of Environmental Protection). So, Dr. Glenn, can you comment on how regional climate modeling like the efforts of New Jersey can help communities and businesses prepare and adapt to the extreme weather impacts of climate change?

Dr. GLENN. Sure, thank you, Chairwoman Sherrill. The regional models that we are, you know, considering for the for the New Jersey area, they're—the critical piece here is that, you know, the sea level is rising for many reasons. In our area, we have the subsidence of the land, which is also very important, and plus that rise that just changes the baseline. And so that's very important for our area. The changes in the rainfall are very important. And the changes in the storm frequency are very important. So you consider those three pieces adding up together is an important part of this.

Chairwoman SHERRILL. Thank you, Dr. Glenn. And, sorry, I kind of cheated. I got you right at the end. And you didn't have as much time——

Dr. GLENN. It's OK.

Chairwoman SHERRILL [continuing]. But we can also add some questions for the record.

At this point, I would like to recognize the Ranking Member of the Subcommittee Mrs. Bice for five minutes.

Mrs. BICE. Thank you.

Several reports show that only a small fraction of satellite data we currently collect is utilized by forecast models. Dr. Petty, what are your thoughts on how we can extract more value from this significant amount of existing satellite data?

Dr. PETTY. Thank you, Ranking Member Bice. I think that's an excellent question from the standpoint that as the report, which is an excellent report, calls out, we need to continue to do work on data assimilation. And data assimilation is a key aspect of how we gain an initial understanding of the state of the atmosphere. So as

we forecast that atmosphere future in time or forward in time, those forecasts become better. Through data assimilation, and through investments of data assimilation, we will be able to take more and better advantage of those satellite observations.

I will also just quickly add that as we move forward in time, there are opportunities to improve those satellite observations. And so as we identify gaps and determine how to fill those gaps, satellite platforms will be one component of that, along with terrestrial observations.

Mrs. BICE. And when you say—when you talk about data assimilation, what is the best way to do that? Are you talking academia, private industry? What do you feel like is a good pathway for that?

Dr. PETTY. Yes, I think that, that pathways across the board, the report points out some efforts to bring the community get together through aspects of things like JEDI (Joint Effort for Data Assimilation Integration), which is a data assimilation initiative. Through that initiative, we're bringing the academic sector together, along with the public sector and the private sector. Some people don't recognize that even in the private sector, there are teams doing data assimilation. So that's an opportunity as well, to bring these scientists together to work on the best solutions.

Mrs. BICE. Thank you. In the coming weeks, I'll be introducing a bill that codifies and expands the National Mesonet Program. The goal is to encourage and incentivize more States to build out or upgrade their systems so that we can have more mesoscale data across the country. Dr. Carr, given your familiarity with the Oklahoma Mesonet, how can we—how can more mesonet observation supplement—wow, I'm off today. Dr. Carr, given your familiarity with the Oklahoma Mesonet, how can more mesonet observations supplement, improve, and add value to the satellite data we currently have? I think your microphone may be turned off, Dr. Carr.

Dr. CARR. I don't know if I ever had it on. Can I have the 5 minutes? No, anyway, I think that's a great question. I'm glad to hear that—what you're about to propose. I think we have 30-something States with mesonets now all trying to match the gold standard that the Oklahoma Mesonet sets, so getting all the States on board would be great.

I think the most important addition that we could add is to add the third dimension to the mesonet program. So they're starting now, but, you know, there's tens of thousands of surface measurements all over the United States. But as soon as you go up 100 meters, there's almost nothing. There's 70 radiosondes, you know, weather balloon stations. So we really need to increase the third dimension and add observing systems like profiling, vertical profiling networks to measure temperature and moisture and wind in the lowest—what we call the lowest mile of the atmosphere. We call it the boundary layer. So an increase in measurements in the lowest levels of the atmosphere in a three-dimensional way would be the most important thing we could do.

Mrs. BICE. Thank you. As all of you know, NOAA is developing and releasing a user-friendly Community Earth System Model. There is also progress toward standing up the Earth Prediction Innovation Center, EPIC, which addresses the research-to-operations challenge by requiring NOAA to leverage expertise across the

broader weather enterprise. How can capabilities like the Community Earth System Model and EPIC be most easily leveraged by academic institutions for research and education? That's open to any of you.

Dr. CARR. Yes, I was very involved in the creation of EPIC. So it's got a great start. We have Raytheon, who got the first contract, and they have a lot of task orders to provide computer support and move the codes to the cloud, provide user support. But what's missing in that contract is that we want the community and the private sector and everyone to be involved in improving the models, but there's no funding for this community. So Raytheon is doing its tasks on users and computer support, technical support, which is really important because we're short on software engineering that they have. But in order for the community to be involved, the private sector partners and the academic partners need funding to do the research needed to improve the models.

Mrs. BICE. Thank you for the witnesses for being here this morning, and I yield back.

Chairwoman SHERRILL. Thank you. And I'd like to bring to the Subcommittee's attention a letter for the record from PJM Interconnection, LLC. PJM is the Nation's largest regional transmission organization, responsible for ensuring the reliability of the high voltage electric grid and planning the expansion of the transmission grid. PJM is regulated by the Federal Energy Regulatory Commission and serves all or parts of the States of New Jersey, Pennsylvania, Delaware, Maryland, Virginia, North Carolina, West Virginia, Ohio, Kentucky, Tennessee, Indiana, Michigan, Illinois, and the District of Columbia. This letter highlights the importance of NOAA's activities as a critical input to PJM's work in ensuring the reliable operation of the electric power grid.

So without objection, I am placing these documents in the record.

Next, I would like to recognize Congresswoman Bonamici for five minutes.

Ms. BONAMICI. Thank you so much, Chair Sherrill and Ranking Member Bice, for hosting this hearing, and thank you to our witnesses.

We know that weather events are increasing in frequency and severity because of climate change, and in the past few years, northwest Oregon has experienced lethal heat waves and devastating wildfires. We also continue to prepare for a potentially catastrophic seismic event off our coastline.

I worked in the past with Ranking Member Lucas and others on the historic and bipartisan *Weather Research and Forecasting Innovation Act,* which is intended to improve weather forecasting and increase Federal weather coordination.

Dr. Glenn, how can improved weather forecasting prepare communities for severe weather events? And how can improved weather modeling deepen our understanding of the consequences of climate change?

Dr. GLENN. Thank you, Congresswoman, for that question. So how can we help the communities prepare? The third pillar of the whole weather enterprise was the information delivery piece of that. That's the critical piece that often gets left off the table, right? Many of the priorities come up at the beginning of the value

chain, at the getting the data to improve our understanding, improving the model and all that. But then we have to communicate with those communities.

And so we see how that's done in places like the Hurricane Center or something like that, where they had that trusted relationship with the emergency managers, and they have the ensemble of guidance that is guiding them. And so we talked to those hurricane centers, and they say, improve the accuracy of those ensemble models. That's the first step that you have to do. And so that's why you always hear us talking about that as that first step.

And then that second step is building that trust with the emergency managers that have the real-time data coming in so they can choose this is the ensemble piece and then this is the piece that we want to communicate.

And then there's all the research on how you communicate with those groups that has to be funded at some point so that we can understand their needs and bring them back. And that's how the requirements flow back through the whole weather enterprise. And so there's this important research on how we communicate, especially in probabilistic forecasts and the longer-term forecasts.

Ms. BONAMICI. I appreciate that. And I remember, and I'm sure Mr. Lucas does as well, all the conversations about the social science of communication and making sure that the message is clear and urgent.

So, Dr. Carr, your testimony and findings from the NOAA study indicate that immediate investments in our weather work force are needed to fill existing gaps so that, in the future, the Nation can rely on a highly technical and diverse work force trained in modern weather forecasting techniques. So, Dr. Carr, what is the existing pipeline for the weather work force, and where is further investment needed? What steps can we take to make sure this work force can be effectively mobilized during times of crisis?

Dr. CARR. OK, thank you. For that question, a couple of aspects to that. One is, is that the research that we talk about that is needed also helps the work force issue so that the professors, researchers have graduate students, and these become the future work force. So when something is really technical like data assimilation, if we provide more research to work with NOAA on this issue and you have more graduate students and postdocs, that will increase the work force.

We, of course, need a lot of software engineering from the computer science component of universities and the private sector. And the issue there is they're very expensive for a government to hire. The private sector will always pay software engineers more, so we need a way for NOAA to have an entity like EPIC that can hire software engineers maybe at the going rate and then help with the IT (information technology) aspect of that problem.

Ms. BONAMICI. Does anybody else have thoughts on how we can bolster the work force? I have 30 seconds left. Dr. Petty?

Dr. PETTY. Yes, absolutely. I think kind of following on to what Dr. Carr has said, utilizing those funds to build partnerships, so, for example, when I talk about the private sector, the private sector is really looking at those partnerships, hey, we can have interns who can be a part of the private sector and learn the technology,

learn the research so that we're working together to build that work force. And I think that's an important approach.

Ms. BONAMICI. I appreciate that. And as I yield back, Madam Chair, I just want to note as well the important issue of the high-performance computing. And I know this Committee has worked on quantum initiatives and others that are so important to this issue. Thank you. I yield back.

Chairwoman SHERRILL. Thank you. And I now recognize the Ranking Member of the Full Committee, Mr. Lucas, for five minutes.

Mr. LUCAS. Thank you, Chairwoman. And I'm going to address my question the entire panel. As I mentioned in my testimony, this Committee will be charged with reauthorizing the *Weather Act* during the next Congress. The report you've highlighted today will undoubtedly inform our deliberations as we think ahead on the topic. Given your respective roles in crafting this report, would each of you highlight one recommendation for this Committee as we consider topics to address in the upcoming *Weather Act?* Just one, and I don't care who starts. And if we have enough time, everybody, our way, gentleman.

Dr. PETTY. I'll be happy to start. My recommendation is found in the report, and that is enhancing our observations, particularly observations of the boundary layer. That's a critical component that we're missing as part of our data assimilation or modeling to make our forecast better.

Mr. LUCAS. Dr. Glenn?

Dr. GLENN. Thank you. I was also going to focus on observations. I think that's a critical part, the Earth systems observations. Many of our networks have been started, have demonstrated value, but they're incomplete, especially our ocean-observing networks. And so completing the existing ones, as we expand out to the new ones that are needed by the new Earth systems models, would be what I would highlight.

Dr. COLMAN. Yes, thank you for the question. As we tried to point out in the report, we don't feel it's one simple answer. It's got to be across the whole board. Having said that, I will call out the information delivery piece. As I mentioned in my testimony, there is an increasing gap between what we're able to produce, the numerical models, and the—what the forecasters then produce and send out than what people are getting and understanding. And we see that in day-to-day weather events where people take the wrong action. And we really need to put that investment in the behavioral and social sciences upfront and make sure we're getting all of the benefit from the other investments in the pipeline itself.

We have underserved and vulnerable populations that—different languages that do not get—currently get the right information and communications. We can't overstate the importance of making sure we complete that process so that they all benefit from the investments that all of you are willing to do.

Mr. LUCAS. Dr. Carr?

Dr. CARR. Yes, so I'll speak up for the computing because as we add more observation capacity, get billions more observations from satellites, which are already planned to go up, as we increase the sophistication of the models and improve data assimilation and

have more ensembles and increase our resolution, you can't do any of that without having the computing power necessary to accomplish it.

Mr. LUCAS. Along that line, Dr. Carr, continuing with you, and clearly it's a concern of several of us on this Committee, how did the problem develop? Did we just not make the right investments at the key moment? How did we get to this point where we need to catch up when it comes to computing power issues?

Dr. CARR. Well, that's a complicated issue. I think we've always been a little bit behind. And the procurement process takes a long time so that by the time you get a new system, there's always systems that are already 10 times faster. And so—and maybe that is the way it is, but the Department of Energy somehow manages to get investments so that they can have exascale systems for at least six of their laboratories. And, as I said in my testimony, I think we should be more ambitious and see if NOAA can become the second place in the country to develop exascale computing capacity. I think you just need to be ambitious and want it, as well as have the resources.

Mr. LUCAS. And I would note for the record, sometimes our questions may seem repetitive, but we as Members tend to hone in on the information that you provide us. We're directed toward the points you make, and such as the computing issue with additional questions, we tend to reinforce where the body of this institution needs to go. Your testimony matters more than you can possibly imagine on occasions like this.

With that, I yield back, Madam Chair.

Chairwoman SHERRILL. Thank you, Mr. Lucas. And I think we have time for another round of questions, so I'll recognize myself for five minutes.

Dr. Carr, you talked about underutilized observations, and I wonder if you could go in—a little bit into that. You also mentioned sustained versus supplemental funding. And it sounds as if—and Dr. Glenn could probably attest to that—a lot of the work we've done has been based on the Sandy Supplemental and now we have the Ida Supplemental. If you could talk a little bit, and then if you want to weigh in, Dr. Glenn, about sustained versus supplemental funding, how the supplemental funding has impacted your research, but then the problematic issues related to not sustained funding. So if you could just start with the underutilized observations you were talking about, what those are?

Dr. CARR. Yes. So with respect to—there's two aspects to underutilized. One is there's a tremendous amount of surface network observations out there, and then a lot of them are not government. So there's this big effort under the National Mesonet Program, to try to gather together all of the service networks that are produced by local and State agencies and there's just thousands of them out there. So we're working to get——

Chairwoman SHERRILL. So since I just have a quick period of time, so you're talking State and local organizations because I know Dr. Petty also mentioned other opportunities, but my understanding is a lot of the private source of weather information is proprietary. And would that be more difficult to share with the government?

Dr. CARR. It could be, but it is being done. And so, in fact, the Nation's Lightning Network is totally private, and NOAA buys those data. So—and the National Mesonet Program is in the process of buying a lot of the surface data because they see that it's worthwhile. And then with satellites, as Dr. Petty mentioned, there's just so many instruments and so many channels producing so much high-resolution data. So every day, about—hundreds of millions of observations are produced by satellites, maybe billions, but the models will use about 300,000 of them so—because there's so much that we just have to learn how to better use them. And that's what we mean by better utilization of satellite data. And as we increase the resolution in our models, we'll be able to use more of it. And we need to have more sophistication in the data assimilation.

And I think the other issue was——

Chairwoman SHERRILL. Funding.

Dr. CARR [continuing]. Funding. Yes, the problem with supplementals is that they're great, they buy us new computers, but it's impossible to do long-range planning because we just don't have the—the annual appropriation is just too little to plan for a really ambitious—the really ambitious computer power that we need. So it's basically a long-range issue—the ability to do long-range planning.

Chairwoman SHERRILL. And Dr. Glenn, if you could talk a little bit about—because it sounds like the year leaves too little, what the supplemental enables you to do as far as weather research.

Dr. GLENN. I think the Sandy Supplemental was an excellent example of how some of these things can get done. The Sandy Supplemental replaced damaged infrastructure, 17 HF (high frequency) radars that were gone that we use for search and rescue every day off the coast. It helped with operations of getting our gliders that Ranking Member Bice talked about out to sea. But what it also supported was the research that helped with the fundamental understanding that started this 10-year activity of working with the Hurricane Center and the groups like Environmental Modeling Center, that got me here to this meeting today. It was through that Sandy Supplemental that that research happened. And that research is being put into operations now. The problem with the operational support for these new activities is that it is also in supplementals. And this year, we are in between supplementals so that hurricane glider fleet that you were talking about is going to be much reduced this year when we expect an overactive hurricane season.

Chairwoman SHERRILL. Thank you. I yield back. Mrs. Bice, do you have any further questions?

Mrs. BICE. One additional question. Dr. Carr, you are very familiar with the National Weather Center in Norman, Oklahoma. Since its opening in 2006, it has brought together all aspects of the weather enterprise, including NOAA researchers, faculty from the University of Oklahoma, local forecasters, and the Oklahoma Mesonet office. How has this model of having different components of the weather enterprise under one roof resulted in better research?

Dr. CARR. Thank you, Ranking Member Bice, for that question. Yes, so I obviously was very involved in the planning and building of the weather center. And we have about 11 weather entities in there, including the School of Meteorology, with its 300 students and 100 graduate students. And I think it's really beneficial for those students to be in the place where the weather knowledge is being put into practice in the Weather Service Forecast Office. And the building is designed so that people can run into each other. The students run into people who wrote their textbooks, they run into the practitioners, the forecasters, they run into the research. They get to have internships and student assistant positions. So it's just wonderful for our students because I would imagine by the time they're seniors, probably over 75 percent of our students have some kind of student employment in one center or the other, the Mesonet or the NSSL (National Severe Storms Laboratory), and that's just a fantastic thing for our students.

Mrs. BICE. And do you think this is something that we should be looking at more collectively as we look to the future for weather research, these types of models where you're bringing everyone together under one roof?

Dr. CARR. Well, yes, I think there's a half a dozen other universities who are co-located with their National Weather Service forecast office. I would certainly encourage more of that. And anytime you have a NOAA laboratory—they do have these cooperative institutes, and there's quite a few NOAA cooperative institutes that are co-located with universities. And so that model is working well, so I think we should continue to support our cooperative institutes.

Mrs. BICE. Excellent. Thank you, Madam Chair. I yield back.

Chairwoman SHERRILL. Well, thank you.

Before we bring the hearing to a close, I want to thank our witnesses for testifying before the Committee today. The record will remain open for two weeks for additional statements from the Members and for any additional questions the Committee may ask of the witnesses. The witnesses are excused, and the hearing is now adjourned.

[Whereupon, at 11:08 a.m., the Subcommittee was adjourned.]

Appendix

Additional Material for the Record

LETTER SUBMITTED BY LETTER SUBMITTED BY REPRESENTATIVE MIKIE SHERRILL

2750 Monroe Blvd
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Michael E. Bryson
Senior Vice President – Operations

June 9, 2022

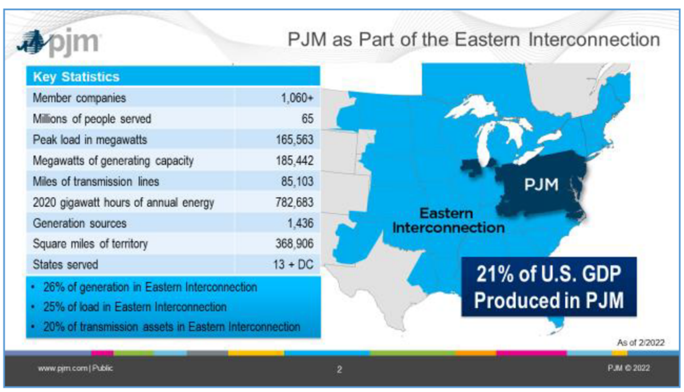
Chairwoman Mikie Sherill
Ranking Member Stephanie Bice
Subcommittee on Environment
Committee on Science, Space and Technology
United States House of Representatives
Washington, D.C. 20515

Re: June 14, 2022, Hearing: 'What's the Forecast? A Look at the Future of Weather Research'

Dear Chairwoman Sherill and Ranking Member Bice:

PJM submits this letter to provide background as to the importance of NOAA's activities as a critical input to our work in ensuring the reliable operation of the electric power grid. We also outline our comments on NOAA's Science Advisory Board's "Report on Priorities for Weather Research" and suggest additional areas for NOAA prioritization.

PJM is the nation's largest Regional Transmission Organization ("RTO") responsible for ensuring the reliability of the high-voltage electric grid and planning the expansion of the transmission grid. PJM is regulated by the Federal Energy Regulatory Commission and serves all or parts of the states of New Jersey, Pennsylvania, Delaware, Maryland, Virginia, North Carolina, West Virginia, Ohio, Kentucky, Tennessee, Indiana, Michigan, Illinois and the District of Columbia.



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PJM Comments on Current Uses of NOAA Data

While the focus of these comments will be related to NOAA data and services related to weather forecast, meteorology, climate, etc., PJM also uses a number of direct services from NOAA, including services providing space weather alerts and forecasts related to Geomagnetic Disturbances (GMD). NOAA space weather data and services are an important part of PJM's reliability response to GMD events. These are incorporated in our operational procedures to mitigate the effects of GMD as well as manage the various notices, warnings, and alert levels

In addition, PJM uses NOAA meteorological data in a number of ways, though largely through several third-party vendors. PJM uses the weather data for situational awareness for hurricanes and extreme weather events. The data is embedded in several of PJM's real-time, control room operational tools such as the Dispatch Information Management Application where weather information is presented in map formats with power grid information overlaid with weather data. PJM also factors in temperature data in our Energy Management system to monitor the ratings or limits on transmission lines that vary with changing weather. In addition, weather data is used in the various long-term and short-term forecasting applications to include load (or customer demand) forecasting, solar generation forecasting and wind generation forecasting. PJM also utilizes the NOAA seasonal Temperature and Precipitation Outlooks that the Climate Prediction Center provides when we perform our seasonal reliability assessments.

PJM Comments on Report on Priorities for Weather Research

PJM does not take exception to any of the recommendations of the Science Advisory Board's Report on proposed NOAA priorities. The report is comprehensive and thoughtful. Rather, PJM wishes to supplement the record by highlighting additional areas where the expertise and research work of NOAA would be helpful to the electric industry's future work in planning for the changing generation resource mix.

1. ***NOAA Assistance to the Industry in Providing Metrics and Benchmarks for identifying Extreme Weather Events –*** In December of 2021, FERC and the North American Electric Reliability Corporation (NERC) issued a comprehensive report of recommendations arising out of the Winter 2021 grid reliability issues in Texas and surrounding regions because of Winter Storm Uri – https://www.ferc.gov/media/february-2021-cold-weather-outages-texas-and-south-central-united-states-ferc-nerc-and. Coming out of that report, the electric industry is currently working on enhanced cold weather and winterization standards to govern both the generation fleet and the operation of the system during the winter months. In developing the standard, the drafters have struggled with the issue of defining "extreme weather" and determining the appropriate measures of extreme but plausible temperature and wind conditions that would trigger an obligation for generators to upgrade their units. NOAA could serve as a helpful resource to the industry in helping to identify those metrics and in advising system operators and others in the industry as well as state and federal regulators on how to best identify plausible but extreme events.
2. ***NOAA Assistance in Developing a Resilience Planning Driver –*** PJM has encouraged FERC to direct a specific planning driver so that regional transmission planners could direct reinforcements to the grid that would enhance its overall resilience. Resilience planning can take many forms ranging from reinforcing existing infrastructure against storm damage to building redundant new infrastructure to ensure a more resilient grid. Key to determining resilient needs in the future is to have sound regionally based information from NOAA as to what changes in weather can be expected in the future. NOAA's assistance to the industry in this area would be

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most helpful. PJM's comments to FERC in this area can be found at https://www.pjm.com/-/media/documents/ferc/filings/2021/20211012-rm21-17-000.ashx and our proposals submitted as part of a FERC Technical Conference on Resilience and Impacts of Extreme Weather can be found at https://www.pjm.com/-/media/documents/ferc/filings/2021/20210927-ad21-13-000.ashx.

3. ***NOAA Research and Assistance to the Industry in the Area of Forecasting –*** The electric generation resource mix is rapidly changing from a heavy dependence on fossil fuel-based generation to increased penetration of renewables including solar and wind. Forecasting has become more challenging as the industry faces a growing number of resources whose performance is dependent on weather conditions. In addition, we are seeing an increased disbursement of these resources throughout the region as "behind-the-meter" resources interconnected at various sites at the distribution level as opposed to concentrated large utility-scale renewable sites. As a result, to the extent NOAA can work with the industry to develop more granular weather and climate information focused on the impact of wind and cloud cover patterns, such information would prove most helpful to the electric industry as it works to improve forecasting of this ever-growing portion of the generation mix.

4. ***Offshore Wind Impacts –*** In addition to general increased penetration of renewable energy, there are plans for significant build out of offshore wind by the end of the decade. PJM and other entities will need access to highly accurate ocean wind speed information at varying altitudes above the ocean surface to improve the forecasting of offshore wind output. Longer-term forecasting and historical data will potentially better inform the best siting locations for the wind turbines themselves as well. There will also be a need for more accurate forecasting of hurricanes, nor'easters, and other extreme storms when they are still off the coast, as these will have significant impacts on the wind production levels.

PJM has had a productive working relationship with NOAA. We have reached out to NOAA to begin discussion on the above topics. In addition, PJM is happy to serve as a resource to this Committee and its Staff as it reviews the future research activities of this vital federal agency.

Should the Committee and its Staff wish to discuss these issues further, please feel free to reach out to me by email or by phone at Michael.Bryson@pjm.com or 610-666-4659 and to PJM Vice President – Federal Government Policy Craig Glazer at Craig.Glazer@pjm.com or 202-423-4743.

Thank you for your consideration.

Very truly yours,

Michael E. Bryson

Michael E. Bryson

Cc: Craig Glazer, PJM Vice President –
Federal Government Policy