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

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

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

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

Weather Forecasting and Improvement

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

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

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

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

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

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

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

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

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

Elsewhere on the modeling and physics front is the FV3, the Finite Volume Cubed-Sphere Dynamical Core, under development at NOAA's Geophysical Fluid Dynamics Laboratory, which incorporates state-of-the-art physics in new ways, allowing for more accurate global forecasts. FV3 is currently being implemented into NOAA's Global Forecast System (GFS) at the National

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

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

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

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

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

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

National Integrated Drought Information System (NIDIS)

I would like to turn our attention now to the National integrated Drought Information System, or NIDIS. NIDIS was authorized by Congress in 2006 and reauthorized in 2014 and 2019 to coordinate and integrate drought research, building upon existing federal, tribal, state, and local partnerships in support of creating a national drought early warning information system. NIDIS aims to improve the nation's capacity to manage drought-related risks by providing the best available information and tools to assess the potential impacts of drought, and to prepare for and mitigate the effects of drought. CIRES supports NIDIS through the seven CIRES/CU Boulder staff members who comprise the NIDIS Program Office, based at NOAA's Earth System Research Laboratory in Boulder, CO.

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

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

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

Backdrop and Context

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

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

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

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

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

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

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