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Testimony of
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Chairwoman Johnson, Ranking Member Lucas, Members of the Committee, I am Berrien Moore, Director of the National Weather Center at the University of Oklahoma. Thank you for the chance to testify at today's hearing on severe weather events, a forum that is timely in its relevance as we are now in the middle of the nation's annual hurricane season.

Apart from these often time catastrophic events, many decisions in important sectors of Oklahoma's and the Nation's economy, such as agriculture, energy, and transportation, depend on weather information. About one-third of the U.S.'s $18 trillion gross national product is generated by industries vulnerable to changes in the weather. Weather and climate information affect every aspect of life and severe weather events lead to serious disruptions with both short-term and long-term impacts on the economy, public safety, and health.

There were 14 severe weather events that caused at least $1 billion in damages in the U.S. in 2018, according to the National Centers for Environmental Information. Dramatic events such as tornado outbreaks such as the ones in Moore, Oklahoma (1999 and 2013), or landfalling hurricanes like Harvey in Houston (2017), Florence in the Carolinas (2018), and Michael in Florida (2018), and Dorian earlier this month as well as the recent tragic wild fires in California all highlight for the general body politic the vulnerability of our society to weather.

The fact that climate is changing adds to the challenge of weather prediction; looking at weather histories is, in a sense, less useful. While it is very difficult if not impossible to attribute a specific weather event to the fact that climate is changing, we can state that the statistical properties of the weather system are changing; stating it more scientifically, the weather system is no longer a relatively stationary process. This fact alone makes the challenge of weather forecasting more difficult and meeting the challenge more important.

We at the National Weather Center understand well and support firmly the National Oceanic and Atmospheric Administration (NOAA) in carrying out its Mission of protecting lives, property and the economy.

We also were greatly appreciative of the Congress for passing the Weather Research and Forecasting Innovation Act of 2017.[1] This bill, which was the first major weather authorization legislation to become law in over two decades, requires NOAA to conduct a two-pronged program; first, to realize "improved understanding of forecast capabilities for atmospheric events and their impacts, with priority given to the development of more accurate, timely, and effective warnings and forecasts of high impact weather events that endanger life and property;" and second, to "collect and utilize information to make reliable and timely foundational forecasts of subseasonal and seasonal temperature and precipitation." Predictions at these time scales are critical for many practical applications, such as water management (drought vs. pluvial years), prevention of vector borne diseases like malaria or west Nile virus, energy management (heating and cooling needs), and especially agriculture.

The leading numerical weather prediction (NWP) models, including the NOAA Global Forecast System (GFS), have exhibited steadily increasing skill over the past 15 years. However, the European Centre for Medium-range Weather Forecasts (ECMWF) and the UK Meteorological Office (UKMO) consistently outperform the NOAA's Global Forecast System. This fact was a

[1] The Bill noted that *Subseasonal forecasting is forecasting weather between two weeks and three months and seasonal forecasting is between three months and two years.* https://www.washingtonpost.com/news/capital-weather-gang/wp/2017/04/04/congress-passes-comprehensive-weather-forecasting-and-research-bill/?noredirect=on&utm_term=.bfe4ee12ce59 https://docs.house.gov/billsthisweek/20170403/HR353.pdf

catalyst in the creation of the Weather Innovation Act of 2017. At its core it recognized that improvements in weather forecasting can come from improvements in

- measurements (Observations),
- ways to ingest these measurements (Assimilation), and
- physical representation of weather processes (Modeling).

Importantly, this Act serves as a guidepost for providing NOAA with the resources to make it happen.

More recently, the National Integrated Drought Information System Reauthorization Act of 2018 (NIDISRA), instructed NOAA to:

- prioritize improving weather data, modeling, computing, forecasting and warnings; and
- establish the Earth Prediction Innovation Center (EPIC) to accelerate community-developed scientific and technological enhancements for numerical weather prediction.

My testimony will now focus on certain specifics that give increased definition to the three foundational elements in numerical weather prediction:

- measurements (Observations),
- ways to ingest these measurements (Assimilation), and
- physical representation of weather processes (Modeling).

Observations. It is my opinion that there are three critical Observational Areas: a) The Next Generation Phased Array Weather Radars that are needed to replace the current WSR-88D radar system; b) Hyperspectral sounding from geostationary orbit to provide vertical profiles of temperature, humidity, cloud condensate over CONUS, and c) a three dimensional National Mesonet to provide even greater insight into the planetary boundary layer.

The Next Generation Phased Array Weather Radars must be dual polarized and all-digital in order to discriminate cloud liquid water from ice and to realize the needed fast scanning that is critical in severe weather situations.

Given the age, costs and capabilities of the current WSR-88D radar system; given a service life extension program (SLEP) for the WSR-88D system, and given the importance of weather and weather forecasting for the country, it seems prudent to establish, fund, and thereby implement a plan to realizing the next generation meteorological phased array radar network. Having completed the extensive service life extension program for the WSR-88D, NWS estimates that it can be reliably operated until about 2040. Estimating that five years will be required for deployment of the new radar network, and allowing for the preceding acquisition effort – requirements publication, contract award, first article development and operational test – it will be necessary to establish validated requirements and the technological base for Next Generation Phased Array Weather Radars by 2028.

The needed research and development, which has its beginning in the Multi-function Phased Array Radar (*MPAR*) project, must be accelerated and focused on the weather-relevant capabilities and requirements. This is central and needs to begin now – with accelerated work commencing in Fiscal Year 2020.

With respect to the collection of hyperspectral data, I believe that NOAA should be given authority to proceed toward an on-orbit demonstration of a hyperspectral instrument at geostationary orbit as a hosted payload. I note that the Weather Innovation Act of 2017:

- requires NOAA to “establish a tornado warning improvement and extension program” that can increase the advanced warning of tornadoes to beyond one hour. (Section 103);
- details Congressional interest in assessing the value of data. . . “from a geostationary hyperspectral sounder.” (Section 107), and
- permits “placement of weather satellite instruments on co-hosted government or private payloads.”

There are multiple reasons why hyperspectral sounding data is needed:

- Time-sensitive information on water vapor transportation both horizontally and vertically (especially in the boundary layer) is key to forecasting severe storms, including deep convective, tornadic storms over the continental US (CONUS).
- Moisture and wind observations are critical for storm prediction through assimilating into regional or storm scale numerical weather prediction models over CONUS.
- Improving the prediction of hurricane intensity and landfall position requires detailed and continuous information on vertical wind profiles.
- Increased destruction and damage from severe storms such as hurricanes and tornadoes are gaining broader public awareness and have heightened public desire to improve our forecasting infrastructure.

Only an advanced hyperspectral sounding instrument from geostationary orbit can provide the needed detailed moisture and dynamical motion information with high temporal and high spatial resolution into the boundary layer. Advanced IR sounders, such as the Atmospheric Infrared Sounder (AIRS) on Aqua and the Cross-track Infrared Sounder (CrIS) on Suomi-NPP (SNPP) and the Joint Polar Satellite System (JPSS) series, do provide high vertical resolution atmospheric sounding information that are already improving the forecast skill in numerical weather prediction models. However, those high-quality measurements are only available in sun-synchronous LEO at a revisit rate of every 8 hours. For ground-breaking severe weather and near-term forecasting of threatening weather in the US, near real-time soundings are necessary to detect changes in the atmosphere as they occur, and this requires a geostationary orbit over CONUS. In the case of rapidly forming tornadoes, minutes instead of hours could mean the difference between life and death.

There is an emerging and exciting pathway to getting instrumentation into geostationary orbit through a commercial communication geostationary satellite as a *host*. The US Air Force was the first to use this approach for their “Commercially Hosted Infrared Payload (CHIRP) and more recently NASA flew the GOLD (Global-scale Observations of the Limb and Disk (GOLD) instrument as a hosted payload in GEO. In fact, NASA intends to fly three Earth Venture Instruments/Mission as hosted payloads in geostationary orbit: the Tropospheric Emissions: Monitoring of Pollution (*TEMPO*), the Geostationary Carbon Observatory (GeoCarb), and the Geosynchronous Littoral Imaging and Monitoring Radiometer (GLIMR).

There is the same possibility for getting a hyperspectral sounder to geostationary orbit between GOES East and GOES West. Combining a host satellite with a HES-like Prototype Instrument payload as a FY 2021 budget initiative would be a “Path Forward” for the US to have a hyperspectral sounder in geostationary orbit much sooner than would otherwise be possible. This would be consistent with the recent NOAA EPIC initiative which seeks both improved measurements and data assimilation into the weather models and is responsive to the Weather Research and Forecasting Innovation Act of 2017.

With respect to the last element of observations, the National Mesonet, it is essential for this Committee to accentuate its strong support for this program and its expansion to provide further innovative means to collect additional data – particularly from the boundary layer. The National Mesonet program has enjoyed strong Congressional support but NOAA budget requests for it continually propose large reductions despite its high value and importance for aiding in improving forecasts for severe weather. A formal authorization of the program by this Committee would be welcome in this effort.

The deployment of small unmanned aircraft systems (UAS) to collect operationally 24-7 *in situ* vertical profiles of the thermodynamic and kinematic state of the atmosphere in conjunction with other weather observations from the National Mesonet (https://nationalmesonet.us) could significantly improve weather forecasting skill and resolution. High-resolution vertical measurements of pressure, temperature, humidity, wind speed and wind direction are critical to the understanding of atmospheric boundary layer processes and directly support and complement the sounding from a hyperspectral sounder discussed above. I believe that the use of UAS will expand rapidly over the coming decade, and the weather community needs to be in a position to exploit that expansion and thereby create a 3D Mesonet.

The Oklahoma Mesonet is of extraordinary value to Oklahoma and surrounding states and this value will be dramatically enhanced by its extension into the vertical dimension. NOAA through its Office for Oceanic and Atmospheric Research needs to expand its UAS program dramatically and thereby establish the foundation for an operational network could be realized to better characterize the atmospheric boundary layer, to identify threats of severe weather, and to improve fundamentally forecast of severe weather. A useful summary of the value of such a 3-D Mesonet was recently characterized by a number of my colleagues at the University of Oklahoma that was published in a recent edition of the journal *Sensors* that was dedicated entirely to the use of unmanned aircraft for atmospheric science investigations.[2]

Finally, regarding Observations, the National Weather Center (NWC) and the Radar Innovations Laboratory (RIL) at the University of Oklahoma are in a leadership position in developing a new generation of all digital, phased-array polarimetric radars. The NWC and RIL house together about 800 people, which includes research scientists, operational meteorologists and climatologists, engineers, technicians, support staff, and graduate students. The researchers based at the NWC are working on a wide variety of projects including radar meteorology, mesoscale meteorology, cloud physics and lightning, synoptic meteorology, and climate variability and change. In addition, within the NWC, the Center for Autonomous Sensing and Sampling, in collaboration with NOAA's National Severe Storms Laboratory, is developing advanced drone-based weather observations. The Oklahoma Climatological Survey (OCS) in the NWC was established by the State Legislature in 1980 to provide climate services to the people of Oklahoma. The Survey maintains an extensive array of climatological information, operates the Oklahoma Mesonet, which is the world leader in ground-based weather observation, and OCS hosts a wide variety of educational outreach and scientific research projects. Finally, given OU's role as the lead institution on GeoCarb, we understand well the challenges and opportunities of hosted payloads as well as the scientific issues associated with the role of the boundary layer in severe weather. We stand ready to help NOAA in the arena of Observations.

Assimilation and Modeling. It is most appropriate to discuss data assimilation into models in the same text as we discuss modeling *per se*. As noted above the European Centre for Medium-range

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[2] Chilson et al., *Moving towards a Network of Autonomous UAS Atmospheric Profiling Stations for Observations in the Earth's Lower Atmosphere: The 3D Mesonet Concept*, *Sensors* 2019, *19*(12), 2720.

Weather Forecasts (ECMWF) and the UK Meteorological Office (UKMO) consistently outperform the NOAA's Global Forecast System. This fact led, in part, to both the Weather Innovation Act of 2017 and the National Integrated Drought Information System Reauthorization Act of 2018 (NIDISRA); the latter instructed NOAA to establish the Earth Prediction Innovation Center (EPIC) to accelerate community-developed scientific and technological enhancements for Numerical Weather Prediction.

Two important events have followed: development of a Working Vision Paper drafted by NOAA Scientists[3] that sets a road map for EPIC and a subsequent Community Workshop in early August 2019. Both the Vision Paper and the Workshop recognized that at the heart of EPIC is the need for a Unified Forecast System (UFS) which would be an end-to-end system for Earth System Prediction that encompasses the assimilation of observations, development of initial conditions, execution of the prediction model, post-processing and analysis of model output, verification of results, and the delivery of products. Obviously, there must be a software infrastructure to support this entire process.

The "prediction model" will be structured around a dynamic core (the Finite-Volume on a Cubed-Sphere or FV3) that was developed by NOAA's Geophysical Fluid Dynamics Laboratory in Princeton. The FV3 core brings a new level of accuracy and numeric efficiency to the model's representation of atmospheric processes such as air motions and was selected in 2017 to be the foundation for the next generation weather models. This capability is at the center of improvements in NWP.

NOAA needs the resources and "encouragement" to move forward with the EPIC Initiative sooner than later. Moving ahead with the EPIC Initiative is of first order importance.

The National Weather Center stands ready to help. The NWC is developing new techniques and novel methodologies for data assimilation and ensemble prediction. Researchers at NWC are applying these techniques from convective scale to global scale in modeling systems to realize a step-change in predictive skill. Importantly, there is a commitment and capability to transition this research and development into operations. Further, the NWC is in a leading position in development of improved convection resolving physics and applications of NOAA's new FV3 dynamic core.

In closing, let me return to the Weather Research and Forecasting Innovation Act of 2017. As the Committee knows well, this Act requires NOAA's Office of Oceanic and Atmospheric Research (OAR) to conduct a program aimed at developing "*an improved understanding of forecast capabilities for atmospheric events and their impacts, with priority given to the development of more accurate, timely, and effective warnings and forecasts of high impact weather events that endanger life and property*." Certainly, the Earth Prediction Innovation Center, which is to be focused on "advancing weather modeling skill, reclaiming and maintaining international leadership in the area of numerical weather prediction, and improving the transition of research into operations" directly address the first charge of the Weather Innovation Act, which deals with high impact weather events. Given that the subject of the Hearing is on Extreme Weather, my testimony has focused more on the first charge in the Innovation Act.

However, the Act also asks for the National Weather Service to "*collect and utilize information to make reliable and timely foundational forecasts of subseasonal and seasonal temperature and precipitation. Subseasonal forecasting is forecasting weather between two weeks and three months and seasonal forecasting is between three months and two years*." I think that Weather Prediction on Subseasonal to Seasonal Time Scales, which sits beyond the range of classic weather prediction

[3] Cikanek et al., A Vision Paper for the Earth Prediction Resource Center, Version 5.0, May 28, 2019

models (less than 10 days) but far shorter than the time scale of climate models (several decades) is an emerging grand challenge in weather/climate prediction.

Given the weight of all these challenges, it seems appropriate for this Committee and the Congress at large to consider the creation of an external, peer reviewed decadal survey process for weather – distinct from that for Earth science because of the more operational nature of weather data.

I would encourage the Committee to have additional hearings on this important challenge.

I appreciate the opportunity to share my views with the Committee and I look forward to our discussion.