Written Testimony of Dr. Frederick H. Carr

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

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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.

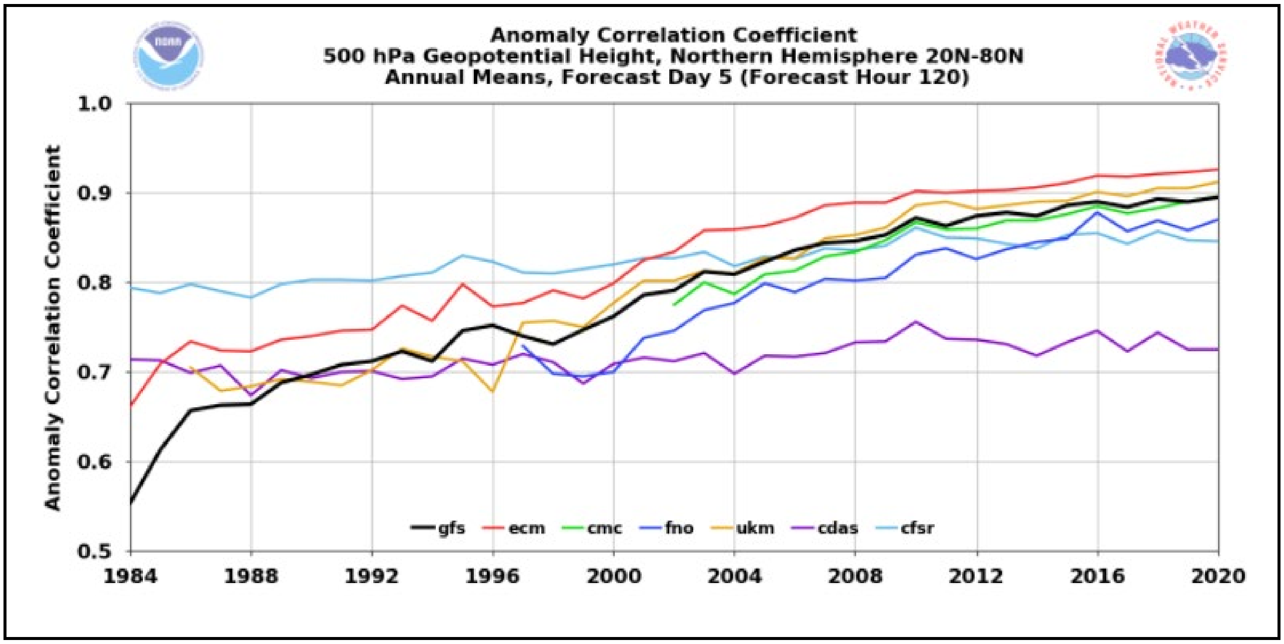

Figure 1: Five-day Forecast Skill of Global Models. gfs: *U.S. Global Forecast System (GFS);* ***ecm:*** *European Centre for Medium-Range Weather Forecasts (ECMWF);* ***cmc:*** *Canadian Meteorological Center;* ***fno:*** *Fleet Numerical (Navy);* ***ukm:*** *United Kingdom Meteorological Office;* ***cdas:*** *GFS used for National Centers for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR) Reanalysis;* ***cfsr:*** *GFS used for Climate Forecast System Reanalysis*[30]

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. Observations and Data Assimilation:

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.