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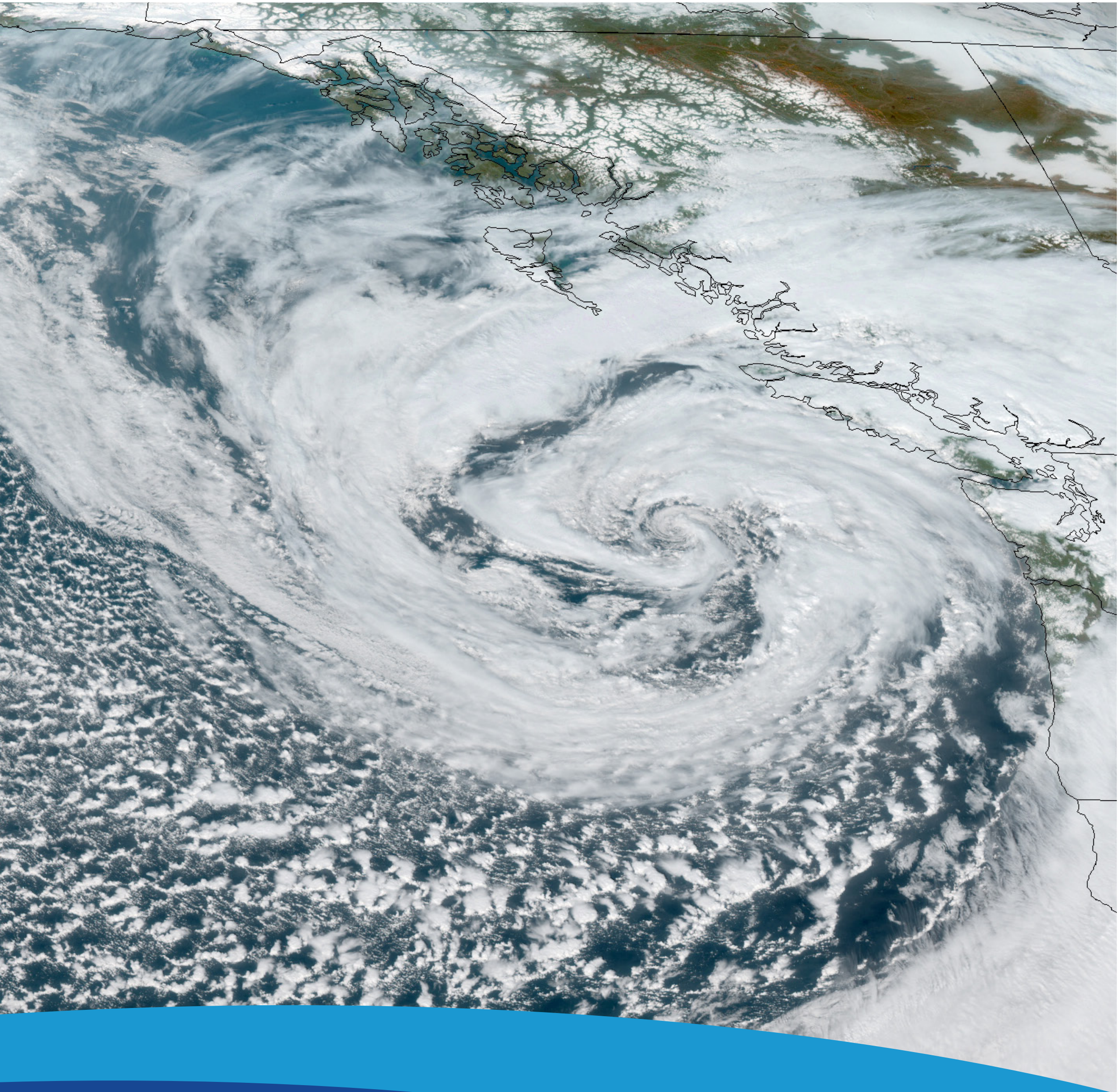



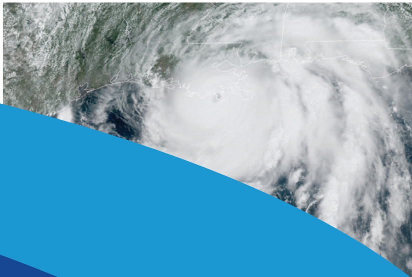

A REPORT ON

Priorities for Weather Research

NOAA SCIENCE ADVISORY BOARD

All images depict weather events and impacts from 2021

Acknowledgments

The PWR Study was both vast and time limited and was only made possible by a broadly collaborative team effort that included in excess of 150 subject matter experts, senior leadership, and SAB members and staff. Key participants included: **John Kreider, Lead, SAB PWR Steering Team,** for his strong leadership and exemplary ability to guide a large project with clear insights and direction. **SAB members,** especially to those who served on the SAB Steering Team and those who provided discussion and invaluable insights throughout the process. **Steve Smith, NOAA Support Team (NST) lead,** and the entire **NST,** for their generous support of the PWR project by creating an extensive document repository and for organizing many critical briefings by many NOAA SMEs. **Task Team Co-Leads (Ann Bostrom, Fred Carr, Mike Eilts, Christa Peters-Lidard, Marty Ralph, Xuguang Wang)** for their commitment, excellent knowledge and expertise, and time and vision, which were critically important throughout the PWR process, from the early scoping and selection of SMEs for the symposia, to the report integration and final writing. **Core Executive Study Team (Bill Gail, Bill Hooke, Zhaoxia Pu, Marshall Shepherd, Bob Winokur)** - provided expert advice through every step of the nearly year long process. **Task Team Members** - for their invaluable participation, including planning and participating in the mini-symposia, developing priority recommendations, and reviewing report results. **External and NOAA SMEs** for sharing their expertise through the mini-symposia and many NOAA briefs. **NOAA Assistant Administrators** for providing their critical perspective during the early framing discussions of PWR. **Cynthia Decker, SAB, Executive Director,** for her overall support of the project through her experience and guidance; the PWR effort benefited from her detailed understanding of the SAB and FACA processes. In addition, staff support from **Tiffany Atkinson** for her support across many PWR teams and activities; **Bonnie Morehouse** for her excellent technical editing contributions; and **Kathryn Olivieri** for her graphic design skills. **Courtney Edwards, PWR project manager**, from the first meetings to the final submission, played many critical roles - she was the project’s communication hub - scheduling literally hundreds of meetings and working alongside the PWR co-leads daily. The project benefited tremendously from her many talents, patience, dependability, and vision. Please refer to Appendix II for a complete list of all who provided time, talent, and commitment to the PWR effort. To all, thank you!!

— Brad Colman and Scott Glenn, PWR Study Team Co-Leads

Conflict of Interest

The Priorities for Weather Research Study Team acknowledges that some members of the Study Team, as well as the external subject matter experts, have had or currently receive funding from NOAA. This was deemed not to be a conflict of interest in regards to their involvement with this report, especially given that the recommendations are not at the specific program level.

Cover Photos

All images depict weather events and impacts from 2021.

Photos beginning in the upper left corner: Damage from a tornado in Livingston, Alabama, March 2021 (Credit: NOAA); Dallas, Texas during unprecedented cold weather, February 2021 (Credit: NOAA); Tennis ball size hail from Milbank, South Dakota, August 2021 (Credit: NWS); Crews clearing brush and dealing with hot spots during California's DIxie Fire, September 2021 (Credit: California Bureau of Land Management); Flash flooding in New Jersey following Hurricane Ida, August 2021 (Credit: Scott Glenn); Dought in Lake Mead, Summer 2021 (Credit: Getty Images); Tornado in Iowa, July 2021 (Credit: Hunter Fowkes); Snowstorm in New York, February 2021 (Credit: Getty Images); Hurricane Ida making landfall, August 2021 (Credit: NOAA); Bomb cyclone off the Northwest coast of the United States, October 2021 (Credit: NOAA).

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1. Executive Summary

In December 2020 Congress charged the National Oceanic and Atmospheric Administration (NOAA) Science Advisory Board (SAB) to publish a report that provides the information necessary to prioritize federal investments in weather[1] research and forecasting over the next decade. In response, the NOAA SAB launched the Priorities for Weather Research (PWR) study, which, through a broad consultative process, engaged over 150 subject matter experts from across the Weather Enterprise to develop this report. The report recommends accelerated and increased investments in priority areas that build upon, and are balanced across, the entire weather information value chain. When taken as a whole, the investments will be transformational, enabling NOAA and the Nation's weather services to meet accelerating weather, water and climate challenges, better protect life and property, and promote greater economic prosperity and environmental justice for all.

The United States (U.S.) has long benefited from a productive and collaborative public, private, and academic Weather Enterprise in its promotion of a vibrant, weather-informed economy, and its defense against severe weather. More accurate and actionable information on everyday weather has grown in its value to the Nation, including wind and solar forecasts for renewable energy, water management for urban, agriculture and environmental needs, and routine forecasts for recreation. With transformational investments, this value will grow even more rapidly in the coming decade, at a time when the United States and the world will depend increasingly on renewable energy sources and are increasingly challenged by weather extremes - including record-breaking heat waves, wildfires, tornadoes, hurricanes, winter storms, and heavy rains and storm surges layered on the top of rising sea levels.

Extreme weather now causes hundreds of deaths and hundreds of billions of dollars in damage annually. The United States is currently experiencing approximately six times as many billion-dollar weather and climate disasters per year than it did in the 1980s.[1] Increasing weather extremes threaten our sources of food, water, energy, and economic well-being, which are all weather dependent and interconnected. These risks fall disproportionately on historically underserved and socially vulnerable communities. Engaging these communities is necessary to identify and address their needs and will strengthen the Weather Enterprise and the resilience of all communities.

Despite excellent progress toward a Weather-Ready Nation[2] and an enhanced weather information value chain, there remain significant gaps and untapped opportunities that this report identifies and responds to with its core set of recommendations. The PWR study identifies an urgent need to accelerate and increase investments across three interconnected pillars: Observations and Data Assimilation, Forecasting, and Information Delivery. The *Observations and Data Assimilation Pillar* includes maximizing the use of existing data sets for additional value; filling critical observation gaps by completing existing networks or establishing new networks that utilize new technologies; and supporting research and training in advanced data assimilation methodologies that are not being supported by other research agencies. The *Forecasting Pillar* identifies the need for foundational Earth system modeling approaches to improve the accuracy and extend the lead time of forecasts (across all relevant time scales); and describes what is needed to improve forecast applications in key critical areas such as water cycle extremes, fire weather and air quality, high impact weather, and coastal processes. The

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[1] Per the Weather Research and Forecasting Innovation Act, weather is defined as ranging from nowcasting (minutes) to seasonal (up to 2 years).

[2] Weather-Ready Nation (WRN) is a strategic outcome where society's response should be equal to the risk from all extreme weather, water, and climate hazards.[2]

Information Delivery Pillar includes the need to support broader and more reliable dissemination strategies; and the collection and analysis of data on weather product use and impact to inform a continuous cycle of improved product development through a user-oriented paradigm. The PWR Report also identifies investment priorities in science, computing, workforce development and the Weather Enterprise that are cross-cutting *foundational elements* supporting the three pillars. In total, the report highlights thirty-three recommendations across the pillars and foundational elements that are summarized in Table 1 below.

The overarching consensus of the PWR Study Team is the urgent need to immediately expand U.S. investments in weather research and forecasting across the entire value chain, and to dramatically increase that upward trend over the next decade. In response, the PWR Study Team has highlighted the following immediate first steps, across four core areas, reflecting an extreme immediate need, or the long lead time required to spin up a critical component. The immediate first steps, a subset of all recommendations (Table 1 below) and critical actions identified by the PWR Study Team, include:

RESEARCH & DEVELOPMENT:

(1) Accelerate development of an **Earth system modeling** approach to improve forecast accuracy and lead time;

(2) Increase investments in **social and human behavioral data collection and sciences** to better understand how weather products are used and to support co-development of improved products;

(3) 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;

INFRASTRUCTURE:

(4) Fully implement and expand rapidly the existing plans for improved **weather data dissemination**, increasing understanding through open science approaches, and expanding applications through weather industry partnerships;

(5) Expand **high performance computing** capacity by two orders of magnitude (over 10 years) to support operational forecasts and data dissemination and provide critically lacking capacity in U.S. weather research;

(6) Fill gaps in existing **Earth system observing networks** with existing, proven or augmenting technologies to expand coverage, especially in underserved regions;

ACTIONS & IMPACTS:

(7) Support **reanalysis and reforecasting** vital to Earth system model evaluation and improvement, to characterize extremes, and provide training datasets for artificial intelligence (AI) product applications;

(8) Target the **understanding and prediction of high-impact weather** to match the urgent need imposed by climate trends, population and infrastructure increases, and disproportionate

impacts on vulnerable communities; including exploring new innovations with AI and machine learning (ML) applications;

(9) Target **water cycle extremes and their cascading impacts** to improve flood and drought prediction and to enable forecast-informed reservoir operations;

NOAA PRIORITIZATION & INVESTMENT:

(10) Develop **improved and increasingly objective methods to balance investments** across the weather information value chain and expand efforts to more precisely target future investments.

These ten recommended first steps provide fertile ground for immediate action and will set the course over the next decade for delivering an even stronger Weather-Ready Nation and a more productive economy.

The PWR Report is an urgent call to action - for Congress, NOAA, and the greater Weather Enterprise. Balanced investments across the PWR recommendations will extend and transform the entire value chain, enabling actions that protect people and property more effectively and equitably from the expanding threats of extreme weather, and that promote a more vibrant, weather-informed and internationally-competitive economy.

PWR Recommendations Summary Table

The PWR Study's thirty-three recommendations and outcomes are summarized in short form in the table below (full text of each recommendation appears in Sections 6 and 7). The recommendations are distributed across the three pillars and the foundational elements of the Weather Enterprise. Each pillar clusters the recommendations into two or three priority areas. The foundational elements are presented as four priority areas: science, computing, workforce development, and The Weather Enterprise.

TABLE 1: PRIORITIES FOR WEATHER RESEARCH - RECOMMENDATION SUMMARY TABLE	
OBSERVATIONS AND DATA ASSIMILATION (OD)	
Priority Area 1	**Use and Assimilation of Existing Observations**
OD-1	Maximize the use and assimilation of underutilized ground based, airborne and marine observations - *to ensure maximum value is derived from the full suite of observations in the Earth system model*
OD-2	Maximize the use and assimilation of underutilized satellite observations - *to ensure maximum value is derived from the full satellite constellation in support of an Earth system model approach*
Priority Area 2	**Advanced Data Assimilation Methods, Capabilities and Workforce**
OD-3	Establish new support of novel methodology research and workforce development for data assimilation - *to advance weather prediction and develop the future workforce*
OD-4	Advance coupled Earth system data assimilation for weather, water and sub-seasonal to seasonal forecasting - *to enable observations in one Earth system component to influence corrections in multiple components*
OD-5	Advance the production of regional and global reanalyses - *to improve detection of extreme events, forecast performance evaluation, improve use of observations*

Priority Area 3	**Observation Gaps and Use and Assimilation of New Observations**
OD-6	Develop and deploy a national boundary layer, soil moisture and aerosol observing system - *to improve research and prediction at the interfaces with other Earth system model components*
OD-7	Observe the ocean, its surface boundary layer, and ocean-atmosphere feedbacks - *to fully utilize knowledge of the ocean as a source of predictability in an Earth system model*
OD-8	Implement a multi-phase program to improve the forecasting of atmospheric rivers - *to better anticipate and mitigate water cycle extremes and their cascading impacts*
OD-9	Fill radar gaps using diverse weather radars and data assimilation - *to better detect significant precipitation and severe weather over a greater area and more equitably across the population*
OD-10	Prioritize smallsat/cubesat observation and data assimilation trade studies and demonstrations - *to define the role of smallsat/cubesat technologies for complementing large satellite systems*
FORECASTING (FO)	
Priority Area 1	**Foundational Earth System Modeling**
FO-1	Accelerate Earth system model development and seamless prediction - *to improve forecasts of all components of the Earth system - atmosphere, oceans, cryosphere, land - on all time and space scales*
FO-2	Achieve the best possible operational numerical weather prediction system - *to provide more accurate weather information to the American public, thus decreasing our vulnerability to weather extremes*
FO-3	Establish a regular, sustained Earth system reforecasting activity - *to enable a more effective cadence and accelerated process for operational model improvements*
Priority Area 2	**Advancing Critical Forecasting Applications**
FO-4	Enhance prediction of Earth’s water cycle extremes - *to improve forecasting of floods, droughts and hydrologic processes*
FO-5	Increase efforts to advance predictive capabilities for fire weather and air quality - *to better inform the public during wildfire events and hazardous air pollution episodes*
FO-6	Improve forecasts of high-impact weather through multisector partnerships - *to provide more accurate and timely watches and warnings for extreme weather events*
FO-7	Advance research on coastal processes in Earth system models for comprehensive coastal analyses - *to improve coastal forecasts of waves, currents, storm surges, total water levels and water quality*
INFORMATION DELIVERY (ID)	
Priority Area 1	**Highly Reliable, High-resolution Weather Information Dissemination**
ID-1	Embrace open science - *to provide uniform access to all communities, support a geographically distributed, diverse workforce, broaden access to talent, and increase agility and innovation*
ID-2	Complete the existing plan to address National Weather Service operational data dissemination challenges - *to solve critical data access and visualization software issues facing weather forecasters*
ID-3	Develop NOAA-wide strategic and operational support for Weather Enterprise data integration and dissemination - *to ensure effective NOAA data sharing and use across all sectors and hazards*

Priority Area 2	**Virtuous Cycle of Collecting and Analyzing Social, Behavioral and Interdisciplinary Observations**
ID-4	Prioritize research on equitable and effective use of hazardous weather information - *to better understand and inform diverse hazard and risk assessment needs, protective decisions and action*
ID--5	Develop and evaluate probabilistic and deterministic hazard information delivery capabilities for diverse end-users - *for rapid dissemination of useful products and to strengthen decision support*
ID-6	Build capacity to collect and analyze baseline and event-specific social and behavioral data - *to learn what weather information is needed when, by whom, and how it can and will be used*
FOUNDATIONAL ELEMENTS (FE)	
Priority Area	**Science**
FE-1	Develop a weather-knowledge ecosystem - *to create, educate, apply and advance weather information synthesis, modeling, automated/human forecasting, communication & decision support*
FE-2	Continue to invest in understanding the basic physics and chemistry of the Earth system - *to ensure that all important processes that affect weather are accurately included in the forecast models*
FE-3	Accelerate the NOAA Artificial Intelligence (AI) Strategy and expand artificial intelligence research - *to provide higher quality and more timely products and services for societal benefits*
FE-4	Greatly increase university involvement in NOAA research - *to gain their assistance in advancing the NOAA mission and in training the next generation of NOAA scientists*
FE-5	Create multi-university research consortia - *to address critical research issues for NOAA*
Priority Area	**Computing**
FE-6	Immediately invest and develop plans for substantially more computing resources - *in order to achieve the goals recommended in this report that are vital to enhance the U.S. Weather Enterprise*
FE-7	Convert, prepare for, and leverage emerging high performance computing architectures - *to keep pace with technological advances and develop the software tools and IT workforce for the future*
Priority Area	**Workforce Development**
FE-8	Develop a pipeline of diverse talent from K-12 students to lifelong learning - *to train and keep current generations of researchers and practitioners in weather science and technologies*
FE-9	Develop an enterprise vision for workforce education and training - *to accommodate different line office needs and leverage existing resources available to the broader community*
Priority Area	**Weather Enterprise Integration**
FE-10	Support a Weather Enterprise data integration and dissemination strategy and sustained operational oversight - *to improve weather data, modeling, computing, forecasting, and decision support*

2. Charge and Response Overview

2.1 Charge from the United States Congress

The U.S. Congress, in the December 2020 FY21 Omnibus Consolidated Appropriations Act, Book 1, page 232, directed the National Oceanic and Atmospheric Administration (NOAA) Science Advisory Board (SAB) to prepare this report on the *Priorities for Weather Research* through the following language:

> ***Report on Weather Research Priorities** - In lieu of House language on a Weather Decadal, the agreement directs NOAA's Science Advisory Board to publish a report, not later than one year after enactment of this Act, that provides policymakers with the relevant information necessary to prioritize investments in weather forecasting, modeling, data assimilation, and supercomputing over the next ten years; and that evaluates future potential Federal investments in science, satellites, radars, and other observation technologies, to include surface and boundary layer observations so that all domestic users of weather information can receive data in the most efficient and effective manner possible*[3].

2.2 Report Structure and Reader's Guide

The PWR Report delivers the information that the U.S. Congress requested and was written to be of interest to several audiences. Section 3 describes NOAA, the National Weather Service and other NOAA line offices, the purpose and scope of the report, and the strategy and approach taken to meet the charge. The report is NOAA focused, yet, it is presented in the broader context of the weather enterprise and the external world. The broader context setting is provided in Section 4, which summarizes relevant trends beyond NOAA that will likely affect the future planning and implementation of the report recommendations.

Section 5 presents five narratives that are used to convey to laypersons the value, and linkages, of the scientific and technical recommendations to follow later in the report. The five narratives should be useful for those readers looking for a high-level understanding of the key issues, real-world needs, and value of the report recommendations.

Detailed findings and recommendations can be found in Sections 6 (pillars), and 7 (foundational elements). The content in these sections is more focused and technical. Congruent with the role of the NOAA SAB, these sections of the report address the charge through the lens of weather research priorities for NOAA, situating these in the broader agency and societal context. The material is necessarily more detailed and technical and should be of the most interest to the technical and scientific leaders across NOAA and other federal agencies.

The report concludes with a summary of immediate first steps that are time sensitive (Section 8) and suggestions for follow-up (Section 9) intended to extend the value of this effort well into the next decade.

3. Introduction

3.1 Overview

NOAA's Mission

NOAA is a science-based federal agency within the Department of Commerce with regulatory, operational, information service, and public safety responsibilities. NOAA's mission is to understand and predict changes in climate, weather, oceans, and coasts, to share that knowledge and information with others, and to conserve and manage coastal and marine ecosystems and resources. This mission is driven by NOAA's service and legislative responsibilities and the resultant social and economic implications for a wide range of industries and coastal communities. NOAA provides the science, service, and stewardship that citizens need to react to and plan for the changing environment around them.

NOAA and The National Weather Service

The mission of the National Weather Service (NWS) is to provide weather, water and climate forecasts, warnings, and impact-based decision support services (IDSS) for the protection of life and property and the enhancement of the national economy. The NWS vision is for a Weather-Ready Nation (WRN), where society is ready, responsive, and resilient to weather, water, and climate dependent events. The NWS goal of a Weather-Ready Nation is supported by eleven mission service areas (Figure 1).

	Weather Ready Nation (WRN)
	Mission Service Area (MSA)
1	Aviation Weather and Volcanic Ash
2	Fire Weather
3	Integrated Water Prediction and Information
4	Marine Weather and Coastal Events
5	Public Weather
6	Severe Weather
7	Space Weather
8	Tropical Cyclones
9	Tsunami
10	Winter Weather
11	Weather Ready Nation Science, Services, and Stewardship Advances

Figure 1: NOAA NWS Mission Service Areas

In its defense against severe weather and promotion of a vibrant weather-informed economy, the United States (U.S.) has benefited from a robust Weather Enterprise[3] that leverages government, private and academic sectors. Multiple federal agencies invest in weather research and benefit from its applications. A growing weather industry supports usage by agriculture, commerce, transportation, energy, and health sectors providing commonly known daily weather forecast updates. A broad-based academic weather research community spans physical, chemical, social, behavioral and health sciences. NOAA, and the NWS, as the provider of most weather observations and forecasts, and as the only federal agency charged to provide weather warnings, are core to these greater enterprise activities, and vital to their success.

While this report is focused on weather research and forecasting, and the central role of the NWS, all NOAA line offices are critical to the execution of the NWS mission. The Office of Oceanic and Atmospheric Research (OAR) is home to significant research that feeds into NWS operations. Collaborations between OAR and NWS are well established as evidenced by the response to the Weather Research and Forecasting Innovation Act of 2017 (WRFIA) and are intended to foster an increasingly robust Research to Operations to Research (R2O2R) cycle. The National Ocean Service (NOS) provides core research and operational functions in the ocean, coasts and Great Lakes, key to the development of

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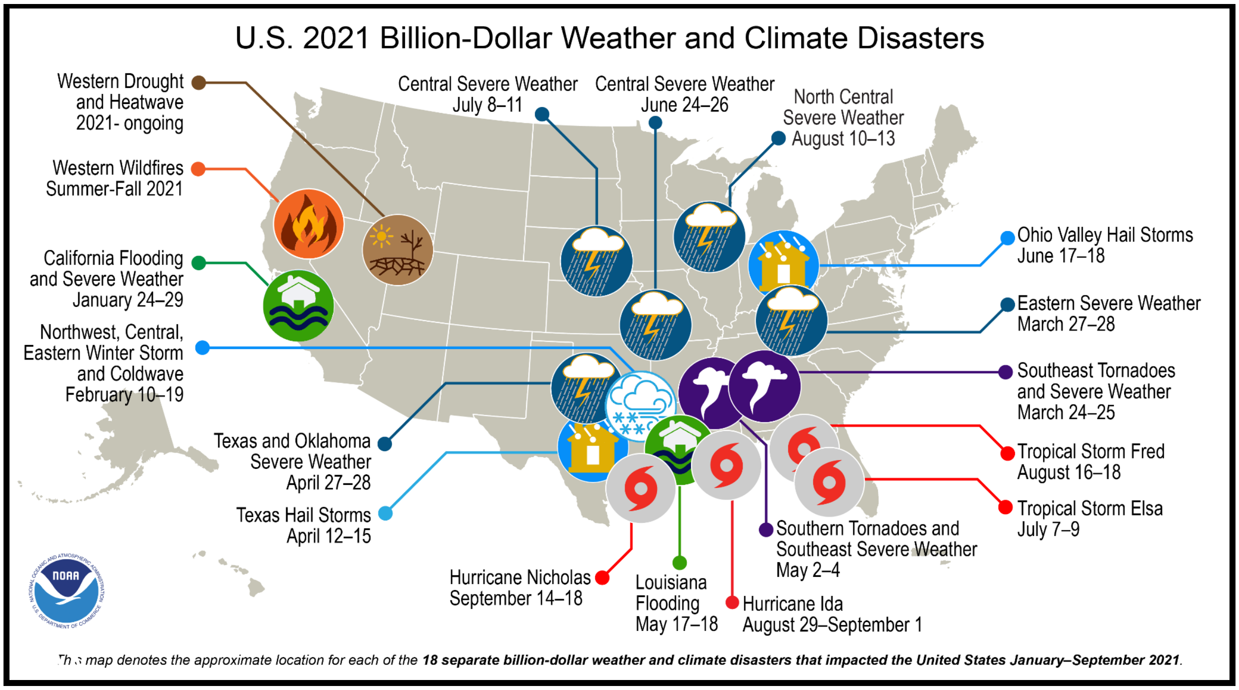
[3] The Weather, Water, and Climate Enterprise, also known as the Weather Enterprise for short, comprises three main sectors that contribute to the science and application of weather and weather forecasting -- academia, government, and America's weather and climate industry.

an Earth systems approach. The National Environmental Satellite, Data, and Information Service (NESDIS) designs and operates satellite programs and provides for the downstream processing of essential satellite data required for research and operations. The Office of Marine and Aviation Operations (OMAO) operates the NOAA ships, aircraft, and an increasing number of uncrewed aerial, surface, and undersea systems (UxS) used for research and operational sampling. The National Marine Fisheries Service (NMFS) is an engaged stakeholder that provides requirements and validation data for physical and biological ecosystem response in Earth system models.

3.2 Urgency, Purpose, Scope, and Strategic Framework of the Report

Urgency for the PWR Study

There is an escalating demand for actionable weather information. In the months after the 2021 Omnibus Appropriations Act was passed in December of 2020, the United States experienced an unprecedented rate of billion-dollar weather and climate disasters.[4] Across the entire United States over 500 lives were lost and nearly $105 billion in damages were caused by severe storms, hurricanes, floods, drought, heatwaves, wildfires, winter storms and coldwaves (Figure 2).



*This map denotes the approximate location for each of the **18 separate billion-dollar weather and climate disasters that impacted the United States January–September 2021**.*

***Figure 2: U.S. 2021 Billion-Dollar Weather and Climate Disasters*[4]**

Billion-dollar weather and climate disasters, tracked in the United States since 1980, have resulted in over 15,000 deaths and over $2 trillion in property damage over the last 42 years. The most common disasters are severe storms (46%), and the most damaging are hurricanes (54%). Some of the deadliest weather is associated with heat waves.[5] Heat related deaths are tracked separately since individual heat waves may not result in billions of dollars of damage. The trends are troubling, with billion-dollar weather and climate disasters increasing in frequency (averaging up to 18 per year) and impact (not

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[4] As defined and tracked by NOAA's National Centers for Environmental Information (NCEI) https://www.ncdc.noaa.gov/billions/.

shown) (Figure 3),[6] and heat waves, with their high death rates, becoming more prevalent with our warming climate.

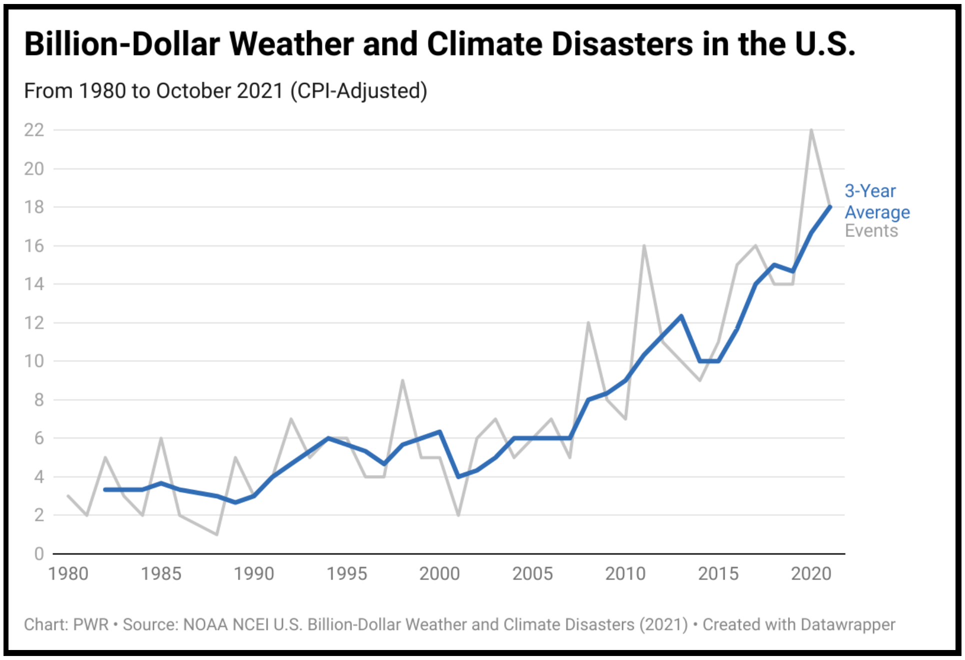

Chart: PWR • Source: NOAA NCEI U.S. Billion-Dollar Weather and Climate Disasters (2021) • Created with Datawrapper

Figure 3: *Annual (gray) and 3-year running average (blue) number of U.S. Billion Dollar Weather and Climate Disaster Events 1980-2021*[1]

Low-income communities, communities of color, older adults, and children are often disproportionately impacted by weather and climate disasters and are more limited in their ability to recover after a disaster.[8] Historically, much of the focus on equity and diversity has addressed issues of access, recruitment, and retention within the federal workforce. While these barriers still require swift and sustained actions, a new landscape within NOAA's portfolio is emerging that must also be addressed. Though not an exact analogue to the disproportionate challenges associated with weather and climate disasters, the environmental justice framework (see Box 1) provides a context for advancing equitable access to weather, water and climate products and services, and is increasingly recognized across the Weather Enterprise. NOAA, as a core element of the Weather Enterprise, plays a significant leadership role in this area.[9]

Box 1: Environmental Justice Framework

Environmental justice is the fair treatment and meaningful involvement of all people regardless of race, color, national origin, or income, with respect to the development, implementation, and enforcement of environmental laws, regulations, and policies. This goal will be achieved when everyone enjoys:

- Same degree of protection from environmental and health hazards, and
- Equal access to the decision-making process to have a healthy environment in which to live, learn, and work

NOAA Perspective

Approaching work within an environmental justice framework is key to improving the accessibility, usefulness and impact of NOAA's science and services.[14]

The NWS has identified a mission critical need to systematically and intentionally engage historically underserved and socially vulnerable communities to achieve the vision of a WRN. Addressing existing inequities in data and forecasts gaps, growing inequities due to the disproportionate impacts of climate change on the most vulnerable communities,[10] and inequities in access to workforce opportunities, are now recognized priorities. Progress requires a) an understanding of the impact of the historical systematic challenges that forced certain groups of people into areas more likely to experience severe weather, extreme heat, flooding, or lack of data coverage,[11, 12] b) social justice and equity filters to be applied to policy, methodologies and projects designed for weather warnings, mitigation strategies and adaptation, and c) co-production of knowledge when approaching and working with communities to improve warnings dissemination and understanding.[13]

Water, food, energy, and national security, as well as economic prosperity (Figure 4) (Figure 4) , for all Americans, are often linked to the impacts of the weather trends, variability and extremes that are increasingly traceable to climate change. The United Nation's Intergovernmental Panel on Climate Change (IPCC) scientific consensus is that the Earth's climate will continue to warm for decades, that sea level will continue to rise for even longer, and that the changing climate will affect weather patterns everywhere, including more frequent and extreme heat waves, droughts, floods and storms.[6] The accelerating climate crisis will be with us for decades as the United States and other national governments develop the policies, technologies and science-based actions required to change global climate trends. This lends urgency to the need for more accurate and tailored forecasts of environmental conditions on time scales ranging from minutes to seasonal to decadal and highlights the need for equitable access to products and services that can better support our more vulnerable communities.

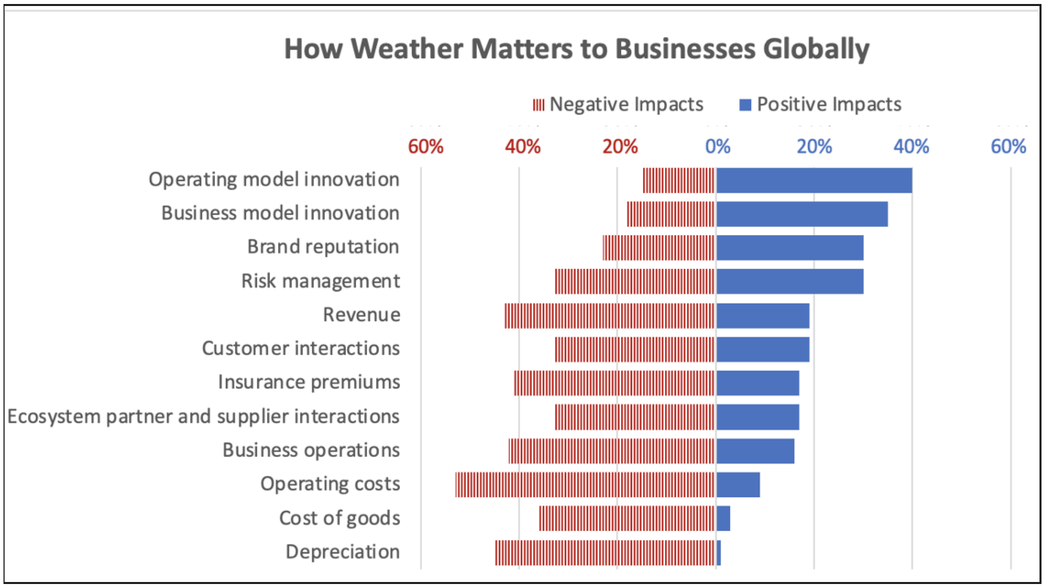

Figure 4: Percentage of executives citing how weather has impacted their business *(IBM Institute for Business Value 2018 Global Weather Study Survey; n=1000, stratified by country from 15 countries). Adapted from Figure 1 of IBM Just Add Weather report.*[7]

The United States' first line of defense in the accelerating climate crisis is the Weather Enterprise, where the key role of NOAA is to foster a broad range of science and technological advances, leverage the vast capabilities of the Weather Enterprise, and together, expand and deliver the foundational core products and services the entire Nation requires for weather, water and climate resiliency, and for greater economic prosperity for all.

Purpose of the PWR Study

The charge to the PWR Study Team - approved by the NOAA SAB on 15 March 2021 - is to "evaluate and provide the information necessary to prioritize potential government investments in a requirements-based framework to advance the United States' weather research and forecasting capabilities over the next decade." Well-informed weather, water, and climate decisions can drive economic prosperity and reduce the toll of extreme weather on the lives and livelihoods of millions of Americans every year. Improved knowledge and awareness of the weather, and weather forecasts, will lead to better decisions, fewer lives lost, greater economic prosperity and a more climate and weather resilient nation. The PWR Report provides guidance on the research and forecasting investments that will enable these improvements, which are crucial for our national welfare.

Scope of the PWR Study

The PWR Study Team identified and evaluated priority areas and potential weather research and forecasting investments to meet the charge given in the FY2021 Omnibus Appropriations Act.[3] Because NOAA is at the core of the Weather Enterprise, and because the study is being led by the NOAA SAB, the focus was on federal investments in NOAA, but with an awareness of what other federal agencies, private sector, academia, and the international community, can provide to advance the research and forecasting priorities. The focus was further refined to emphasize weather time scales as defined in WRFIA as ranging from nowcasting (minutes) to seasonal (up to two years).[15] The PWR Study Team concentrated on identifying, evaluating, and recommending high priority investments; primarily emphasizing future and planned investments, while acknowledging the need for continuing support of existing investments within the context of the PWR Study scope. An unavoidable outcome of this approach is that many existing and highly valuable programs and applications are not explicitly identified or discussed. As such, the PWR Study Team urges readers to put weight only in the identified priority areas as timely and critical for future investment and to not make any assumptions about the value or importance of those programs not mentioned.

Strategic Framework of the PWR Study

The PWR Study Strategic Framework (Figure 5) is based on three principal pillars representing NOAA's role in the development and delivery of weather information and its underlying foundational elements. The three pillars are: observations and data assimilation; forecasting; and information delivery. The arrows in Figure 5 are critical. The right-to-left arrows indicate the driving influence that mission service area requirements have on the process. The resulting product flow is left to right. This feedback loop is crucial to maintain mission focus and ensure system improvements. Science, computing, workforce development, and the Weather Enterprise are cross-cutting foundational elements for all three pillars. The four foundational elements support the pillars that enable the protection of life and property, economic prosperity, and equity in weather information development and delivery. This framework provides the structure by which NOAA can achieve its Weather Enterprise objectives.

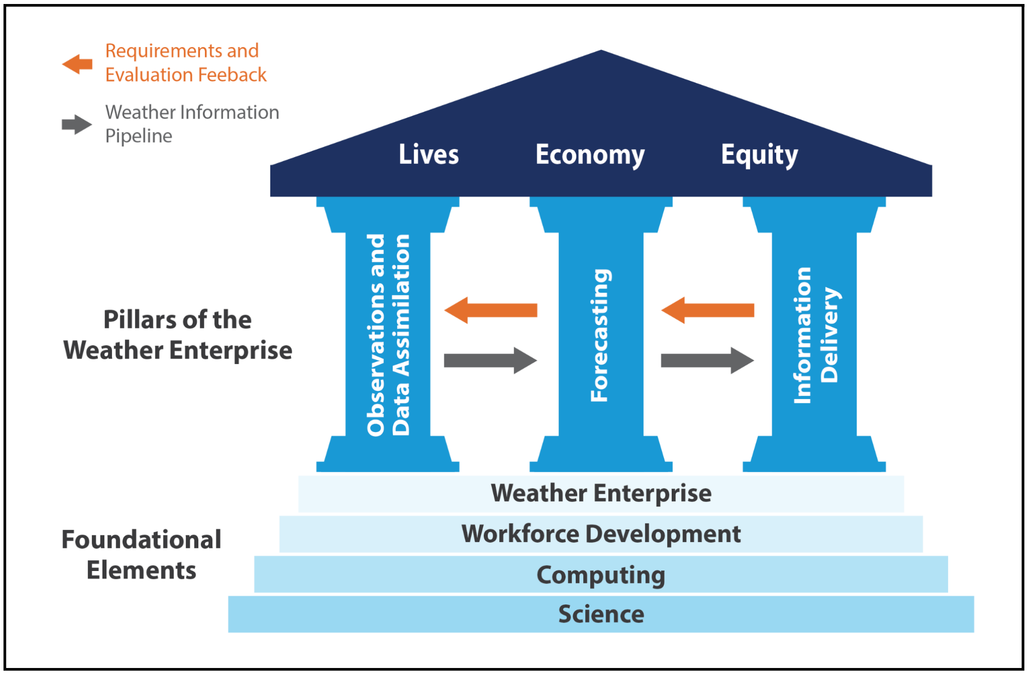

Figure 5: Priorities for Weather Research Strategic Framework

3.3 PWR Study Prioritization - A Consensus Approach to Delivering a Balanced Portfolio of Recommendations

The scope of investments necessary to support the overall advancement of weather for society is vast. All the priorities identified within this report are important and each would have material benefits for the Nation's understanding and forecasting of, and resilience to, weather. The identified priority areas cover a broad range of topics from observations, to basic science, to modeling and computing, to data distribution and equity, which makes it difficult to weigh the trade-offs in one investment against another. For example, are investments in new cubesat observations more effective than acquiring additional computing to support high-resolution ensemble models? Such decisions are complicated yet can have profound consequences for improvements in weather forecasting science. In order to optimize the return on the Nation's investments in the Weather Enterprise, a structured analytical approach with clearly identified methods and tools is needed to support objective investment decision making. While this approach is beyond the scope of this study, NOAA is urged to invest in such an approach as they immediately embark on the first steps of considering and implementing the recommendations within the report.

The charge in the FY2021 Omnibus Appropriations Act is to "publish a report ... that provides policymakers with the relevant information necessary to prioritize investments in weather forecasting, modeling, data assimilation, and supercomputing over the next ten years." The PWR Study Team has made every effort to meet and align with this charge. In addition, for the PWR Study, it should be noted that a review of NOAA's budget formulation process was not part of the report preparation. Rather, early in the study process, the PWR leadership team provided guidance to the Task Teams, who were the core information gathering teams (see Figure 16), on what should be considered "high priority" throughout the discussion and compilation process by all teams. For this study and report, a high priority recommendation is defined as one that:

- Has high reward and benefit (gap filling, core, or innovation) with a clear connection to value, impact, or transformational potential
- Has a strong linkage to NOAA through identified requirements (i.e., through NOAA's Technology, Planning and Integration for Observation (TPIO) process or relating to NOAA's Government Performance Results Modernization Act (GPRA) goals, or alignment with NOAA mission service areas or the Weather Research and Forecasting Innovation Act (WRFIA).
- Reflects a favorable balance between probability of success and reward
- Is clearly advantageous (value, impact, or transformational) to achieving NOAA's weather mission
- Has a favorable context with respect to the Weather Enterprise and the changing external world

The above-described criteria were applied using the consensus approach across the Task Teams efforts to guide the overall findings and recommendations of the study. Additional considerations and context include:

- Given the broad scope, and limited time and resources, it was not possible, nor required given the Act's charge, to develop and apply a ranked prioritization process.
- The report leans heavily upon a consensus process with input from more than 150 subject matter experts (SME) with broad experience from multiple sectors (Table 2).
- The Task Teams had extensive prioritization discussions, reviewed over 100 documents of NOAA-provided material, received sixteen NOAA briefings, and held three symposia with seventy presenters for additional vetting of topics. It is likely that the results are reproducible with comparable effort and a similar range of participants.
- This process was established to optimally inform a federal investment strategy with a balanced approach to identifying probability of success and reward for investments. Readiness level and timing were important, and teams were charged to target a balanced portfolio of readiness level efforts distributed across a decade-long vision.
- The priorities are not ranked at the individual level; however, sufficient discussion, vetting, and reduction of scope have resulted in sets of priority recommendations with essentially equal weight. Near the end of the report, the section on *Immediate First Steps* provides critical information on timing considerations for execution of the overall strategy. For example, efforts for which there are subsequent dependent recommended activities are called out.

PWR Subject Matter Experts	
PWR Team	39
NOAA	62
External	58
TOTAL	159

Table 2: Priorities for Weather Research Subject Matter Experts

The recommendations provided in this report are intended to build upon NOAA's essential core role within the weather enterprise, with a focus on building a Weather-Ready Nation. They also target strengthening the weather enterprise as a whole. Taken together, they provide a plan to inform and enhance NOAA's and the Nation's continued investment in a comprehensive weather program with the goals of improving forecasting, protecting lives and property, supporting our economic well-being, and providing equitable access to weather products and services.

4. External Context - Overarching Trends, Environmental Equity, and Risks and Opportunities

NOAA's strategies and plans are best developed and implemented with an eye on conditions external to NOAA, referred to here as the "external context." This context starts with the needs and vulnerabilities of NOAA's customers, extends to the roles and activities of the larger Weather Enterprise, and ultimately encompasses general aspects of society such as technology advances and education processes. NOAA does not develop mobile devices, for example, but their evolution has an enormous impact on how people access and use NOAA's work. Understanding this external context is important as it reflects: a) resources and technological advances that NOAA can leverage, b) constraints (such as workforce availability and capability) within which it must manage, and c) growing needs (such as supporting underserved populations) that it must meet. Within a ten year plan, anticipating trends is particularly important for understanding context.

This study lacked the resources to do a comprehensive survey of such context issues, but it can raise awareness and provide some guidance to motivate further NOAA thinking on the topic as they develop their plans. A detailed summary is provided in Appendix III.

Continuing to successfully deliver on its service mission in a budget constrained environment is not a new challenge for the NWS. The National Research Council's 2012 *Weather Services for the Nation: Becoming Second to None* (Second to None) study identified "keeping pace with new advances in science and technology, meeting expanding and evolving user needs, and effectively partnering with an increasingly capable Weather Enterprise" as key challenges.[16] These still hold today. Context topics that are expected to have a particularly important impact for NOAA over the coming decade include:

- **Cross-Disciplinary Science.** Science is increasingly cross-disciplinary, requiring expanding collaborations across Earth system science, social and behavioral sciences, space science, and other sciences for transformative progress. Reflecting this transformation into NOAA processes isn't simple and requires focused attention.
- **Rapid Technology Advances.** The external world is making enormous technology advances, such as new observing systems, forecast models that can take advantage of rapidly advancing high performance computing (HPC) and cloud computing capabilities, and mobile devices for interactive information dissemination. NOAA may be able to leverage many of these with less or even minimal additional resources of its own.
- **Growing Extent and Diversity of Use Cases**. We are increasingly an information-driven society, and NOAA's information is a central element. The number of use cases is expanding rapidly, and novel uses emerge regularly. There is a growing need to integrate information from diverse sources, and for the inclusion of social science to redefine how information is best communicated.
- **Limits to Resources and Increases in Natural Hazards.** The National Academies has noted the growing role of environmental change, including change we increasingly cause ourselves, pushing us to seek new ways to thrive as our environment context becomes less certain.[17] We see this in the growing prevalence of wildfires across the western United States, the challenging vulnerability of coastal communities to hurricanes, the increasing severity of flash floods across the eastern United States, and the first formal water shortage in Lake Mead.

- **Role of Weather Enterprise Partners.** The Weather Enterprise is an enormous amplifier for NOAA's limited resources, greatly expanding its societal impact. Partnering with the Weather Enterprise runs the full range of the NOAA information pipeline, from operational data collection and dissemination, to improving forecast models and data assimilation, to delivering tailored products to user communities. The Interagency Council for Advancing Meteorological Services (ICAMS), the American Meteorological Society (AMS) and other organizations can provide important networking and coordination for the enterprise.

Important topics emerge regularly, and the priority of existing topics evolves. Among those societal topics of growing priority to NOAA is environmental equity. Key aspects include:

- **Weather and climate change impacts on underserved and marginalized communities.** There is a disproportionate impact of climate change and high-impact weather, for example heat waves,[18] on already underserved communities. Issues of justice, equity, diversity and inclusion are paramount. The need to close gaps in data coverage and communication for less-served communities is now recognized as required for a more inclusive WRN.
- **Equitable Access.** To ensure NOAA services are easily accessible to everyone, and that access to opportunities within NOAA is equitable, requires increased attention to diversity and inclusion.

External context often reflects risks that should be identified and managed and opportunities that should be grasped. New risks will arise during the next decade that will challenge business-as-usual approaches to NOAA's mission to protect lives and property and promote economic prosperity. Opportunities will appear that can augment NOAA resources, but they need to be anticipated. Examples include:

- **Evolving Aspects of Climate Change.** Climate change, and its impact on weather and water variability and extremes, produces new vulnerabilities and the need for improved weather forecasts to maintain water supply, food, and energy security as well as economic prosperity.
- **Keeping Pace with Technology.** Keeping pace with advancing science and technology requires a nimbleness that may require rethinking the integration of operational requirements and research. Networking, partnerships, and similar initiatives can improve access to external innovations in academia and the private sector.
- **Cybersecurity.** Critical operations are increasingly targeted by hackers and other disruptive entities. Failure to stay ahead can have devastating operational consequences.
- **Workforce Challenges.** Staying nimble requires a workforce with a broader and evolving range of technical skills and spectrum of talents. Future workforces will include meteorologists working with other experts in Earth sciences, HPC, artificial intelligence (AI) and machine learning (ML), observing, data assimilation, modeling technologies, social sciences, etc. Strategies to increase the workforce capacity will be essential given the increasing demands for these skills.
- **Uncertain Budgets**. The NWS is transitioning from a production-focused operational model defined by what operational products it can provide, to a user-centric model defined more by what is required by multiple user communities. This transition is difficult in a budget constrained environment that requires end-to-end thinking on how to reliably provide services that meet core needs and where existing products and services must be maintained while new products and services are developed, tested and deployed.
- **Dependence on National and International Partnerships.** Serving the United States' needs for global transportation, goods and services, and the need for longer term forecasts that depend on global observation networks, increasingly require international collaboration through existing

pathways such as the World Meteorological Organization (WMO) or the Intergovernmental Oceanographic Commission (IOC).

This report was prepared with attention to external context and how it will influence NOAA over the coming decade. As NOAA plans and implements its programs, identifying external context issues, and anticipating trends in external context, can greatly enhance NOAA's impact and the effective use of its limited resources. Flexibility is an important organizational attribute for responding to both opportunities and risks from changing external context.

5. Narrative Themes

There are five narrative themes presented in this section and shown in Figure 6, that highlight the broad societal benefits delivered by a focused and well-supported National Weather Service. Each of these narrative themes will be used as examples to highlight the motivation and value of several key identified recommendations. The high-level and illustrative context - or storyline - will directly relate recommendations to impacts, benefits, etc. As such, they will communicate the "Why?" motivation for the recommendations.

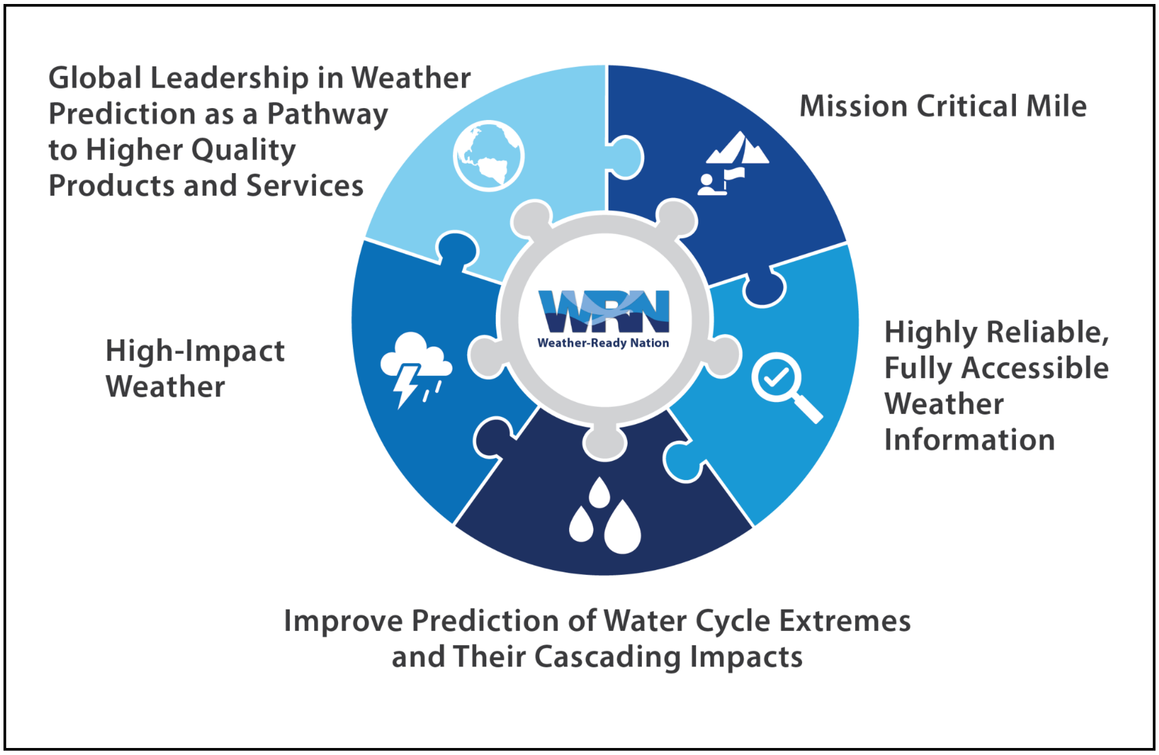

Figure 6: Narrative Themes supporting a Weather-Ready Nation

5.1 Mission Critical Mile

NOAA and Weather Enterprise investments into weather information development and delivery sciences have produced remarkable results in the quality and reliability of weather forecasts and information. Success, however, cannot be measured by the accuracy of forecasts alone, but must be judged also by the societal response to those forecasts and, ultimately, the resulting societal value and outcomes. At the heart of NOAA's mission is sharing knowledge and information with others—including scientific understanding and predictions of changes in climate, weather, oceans, and coasts (ID-6). The mission critical mile was for many years termed "the last mile" but it is now clear that it is equally the "first mile."

Over the last century evidence has accumulated that to share knowledge and information effectively requires an understanding of the beliefs, contexts, and capacities of those with whom the information is being shared.[19-22] Technical forecasts can be uninterpretable for non-experts. Technical weather information developers often do not know all the informational elements that a decision maker needs to make a decision; for example, tornado warnings with short lead times may not be actionable for those in mobile homes.[23] Understanding audiences—in other words, navigating that "first mile" —is crucial to reaching them.[21] More recently, communications research and other social sciences have pointed to community engagement and co-production as critical pathways for effective development and dissemination of actionable knowledge and information, and essential for effective environmental management.[24-25] Effective information development includes forecast and observing system design and optimization that responds to user needs, creating a critical feedback loop between the system and user responses.

NOAA faces a dearth of systematic data on the people who make up the forecast and warning system and on the communities they serve, which is in stark contrast to the wealth of accessible atmospheric and other environmental data.[26] This gap makes it impossible to develop critical knowledge about weather information uses and needs, much less to track changes over time as new data, products, policies, and programs are implemented.

NOAA investments in impact-based decision support services (IDSS)[27] have demonstrated value,[28-29] yet forecasters and others in NOAA still lack some of the data and tools necessary to fully understand the evolving needs of diverse populations of emergency managers and other partners they are tasked to support. Current approaches to developing weather forecasts and related risk information tend to be opportunistic and *ad hoc*, driven by hydrometeorological and ocean science information development, high-impact events of great consequence, and inferences and assumptions about users' needs. Opportunistic data collections from grant-funded social science research efforts are filling gaps but are not sufficient to enable NOAA to meet its broader weather information delivery goals.

The complexity of weather information delivery in rapidly changing information ecosystems,[21] together with the increasing urgency of extreme environmental event management and communication needs makes accelerating NOAA's approach imperative.

Investing in mission critical mile research (ID-4 to ID-6) will enable NOAA observation, data assimilation and forecasting efforts to be driven by evidence about users' needs and barriers, which, in turn, drive the development and delivery of weather information and atmospheric research, conceptually, structurally and culturally. This new paradigm enhances development and delivery of user-oriented, timely, meaningful, skillful (accurate), usable, and actionable weather information. It requires enterprise-wide systems and structures to advance, expedite, and regularly evaluate the development and delivery of user-oriented information, address inequities in current service delivery, and reduce adverse impacts on communities.

5.2 Global Leadership in Weather Prediction as a Pathway to Higher Quality Products and Services

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 the science can achieve. For example, verification of global model forecasts (see Figure 7) 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 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. 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.

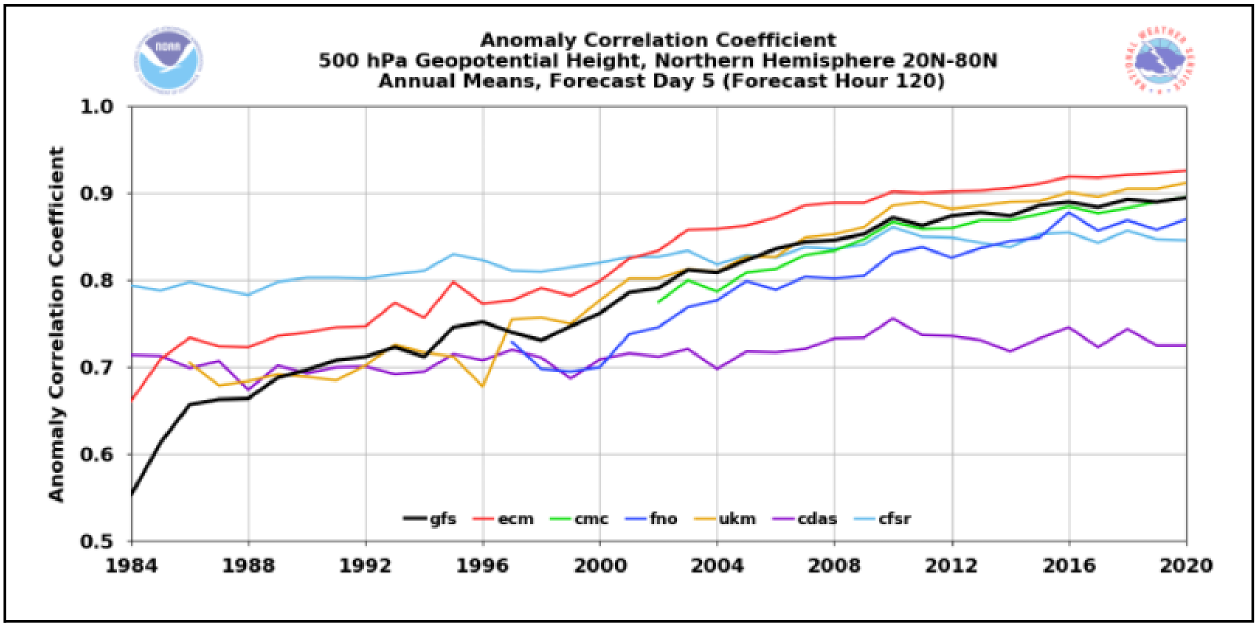

Figure 7: Five-day Forecast Skill of Global Models. gfs: *U.S. Global Forecast System (GFS);* ***ecm:*** *European Centre for Medium-Range Weather Forecasts (ECMWF);* ***cmc:*** *Canadian Meteorological Center;* ***fno:*** *Fleet Numerical (Navy);* ***ukm:*** *United Kingdom Meteorological Office;* ***cdas:*** *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 improvements needed for the United States to gain global leadership in weather prediction are well known. However, there is no simple "silver bullet" solution - major investments are needed in several areas:

First, observation gaps in existing networks should be addressed, especially in the planetary boundary layer (PBL) and for observations targeted on sampling high-impact weather and water cycle extremes (OD-6 to OD-10). For example, increased density of observations just above the surface would lead to better timing and tracks of severe thunderstorms. It is also vital to more effectively utilize existing observations (OD-1, OD-2) and to perform basic research on innovative data assimilation (see definition of data assimilation and its impact in Section 6.1) methodologies (OD-3 to OD-5).

Second, it is increasingly evident that further improvement in weather modeling requires a more comprehensive treatment of the entire Earth system. Thus, a community, multi-scale, coupled ESM (see Box 2) is required to become the backbone for operational weather forecasting (FO-1). This would improve short-range forecasts of weather extremes as well as seasonal forecasts of, e.g., droughts and dry weather patterns that lead to wildfires.

Box 2: Earth System Model

An Earth system model (ESM), as used in this report, is a mathematical model of all the important 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. The ESM is solved (projected forward in time) by supercomputers to produce weather forecasts and climate simulations. A state-of-the-art climate model is an ESM. 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 8-10 days), that these omitted processes are important to medium-range forecasts. Thus this report advocates 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.

Third, major investments are required in computing resources, including cloud computing, next generation computers, storage, and bandwidth, especially for research computing, but also for the operational implementation of more comprehensive models (FE-6). Without increased computing resources, none of the recommended new models and data assimilation that improve the forecasts will be able to run on time.

Finally, the above improvements cannot be accomplished without:

- investments in developing the next generation, multi-disciplinary workforce with expertise in modeling, observing systems, data assimilation, high performance computing, big data, AI and the social sciences (FE-8)
- an increase in extramural support with a longer term, forward-looking view to engage the community (FE-4)
- multi-sector partnerships to leverage expertise in other agencies, academia and private enterprise (Section 7.4)
- reliable and resilient access to NOAA weather data and information for enterprise integration and dissemination (ID-2, ID-3)
- advancing knowledge on how to deliver equitable forecast guidance to improve how the public receives, interprets and responds to weather information (ID-4)

The outcome of these investments will advance U.S. global leadership in weather forecast skill that will better serve the American public. In addition, these investments are in direct support of the aspiration goal of the 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.” These benefits will range from improved seasonal forecasts of wet, dry, warm and cold periods to forecasts of local severe weather and flooding events, increasing public forecasting skill across all NOAA Mission Service Areas, and leading to improvements in all subsequent products and services - that is, a more Weather-Ready Nation.

5.3 High-Impact Weather

The vision of the NWS is a *Weather-Ready Nation*, in which the population is prepared for and responds safely to weather, water, and climate-dependent events of all kinds. High-impact weather (HIW) includes extreme events such as severe thunderstorms (tornadoes, hail, lightning, downbursts), hurricanes (winds, surge, inundation), flooding, blizzards, cold and heat waves, ice storms, fire weather, dangerous air pollution, etc., that, over the past 5 years (2016-2020) have caused an average of over 790 deaths and $125 billion in damage per year.[31] Figure 8 shows examples of the devastation caused by HIW. Owing to climate change and increases in population and infrastructure, the severity and impacts of HIW are expected to increase in the future.[6]

Figure 8: 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.*

It is important to note that while the extreme events listed above get the headlines, everyday weather has enormous economic impacts, often beneficial. In fact, essentially all facets of weather information - from benign temperature swings to variability in cloud cover, wind direction, and space weather events - can have big economic impacts within specific industries (e.g., brisk winds and sunny skies enable billions of dollars annually in energy production by wind turbines and solar arrays). Fortunately, actions recommended here (and in Section 5.2 above) will also lead to improved forecasts for everyday weather.

While NOAA is providing valuable forecasts of HIW today, there are gaps in its capabilities: lack of accuracy in predicting hurricane intensity, flash flooding events, local rainfall and snowfall intensity, spread of wildfires, and anticipating which severe thunderstorms will become tornadic. Is it possible to address these forecast challenges to achieve more accurate, longer lead time, and trustworthy HIW forecasts? The answer is yes, provided the following four high priority actions are taken: Increase observations of HIW environments (OD-6 to OD-10), advance numerical models and data assimilation systems for HIW phenomena (FO-6, OD-3), greatly increase computing power to enable timely high-resolution forecasts (FE-6), and seek improved ways to deliver information to the public that results in safe responses (ID-4) (see Box 3).

Box 3: “Warn-on-Forecast”
As an example of what is needed to improve HIW forecasts, consider the warnings for tornadic thunderstorms, which today are based on observations. The NWS “Warn-on-Forecast” vision[32] 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 four of the high priority recommendations, 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 as outlined in FE-6, and d) research 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.


Woolsey Fire seen from Topanga, California, in November 2018. Credit: Peter Buschmann.

We also wish to highlight a rapidly emerging threat to life and property - wildfires. Due to climate change and population increases, wildfires and their impacts are increasing across the globe, thus increasing the need for and importance of fire weather forecasts. Also, wildfire smoke and many other sources of air pollution highlight the need for smoke and air quality (AQ) forecasts, which have high societal and economic value in preventing and mitigating discomfort, illness and mortality. Reliable predictions of fire, smoke and pollutant behavior and spread remain challenging with current operational systems, but are critical for decision support for evacuations, power shutoffs, public health advisories, and other incident responses (FO-5). Moreover, poor AQ disproportionately affects minority and underserved communities, creating service equity challenges for NOAA.

5.4 Improve Prediction of Water Cycle Extremes and their Cascading Impacts

The water cycle is the most tangible way that weather connects with people: from beneficial impacts of rain and snow, to the adverse impacts of too much or too little. These extremes can cause water restrictions, crop failures and wildfire during times of drought to evacuations, property damage, fatalities and even loss of communities during floods. Observing, predicting and responding to extremes present unique challenges to our weather observation and prediction system, and delivery of actionable information. Droughts and floods are both deadly (more-so than other storm types) and costly: $6.4 billion and $3.8 billion per year, respectively,[31] and much more if their true role in other disasters (e.g., hurricanes and wildfires) were considered.

Left: Drought-stricken landscape (Credit: NOAA). Right: Flooding in Venice, Louisiana two weeks after Hurricane Katrina (Credit: Lieut. Commander Mark Moran, NOAA Corps, NMAO/AOC).

Another major challenge stems from the rapid swings between these extremes, which are becoming more evident and are projected to be an increasing part of the future, including longer and deeper droughts, punctuated by larger floods. A promising approach to help address this climate change risk has emerged that creates new ways to operate existing reservoirs more flexibly, through forecast-informed reservoir operations. The more skillfully precipitation and streamflow extremes can be predicted, the more flexibility there could be to hold water after a storm, or to release it ahead of a storm. This would expand the ability to use trillions of dollars of existing dams as a climate change adaptation capability.

Unfortunately, precipitation forecast skill has not improved substantially over decades (Figure 9) and remains one of the major technical challenges in atmospheric sciences.[33] Poor prediction skill for flood and drought has an inordinate impact on disadvantaged communities whose risk exposure (e.g., housing in flood plains) and disparities in information services (e.g., Next Generation Weather Radar (NEXRAD) gaps) present barriers to success.

These factors make accurate prediction of water cycle extremes and their cascading impacts of critical national importance, which was recognized by the multi-agency Office of Science and Technology Policy (OSTP) 2020 report "Earth System Predictability Research and Implementation Roadmap," which identified this goal as the leading priority, including recommendations to improve observations, physical process understanding and prediction systems to achieve these goals.[34] Many other relevant national reports have been developed that point to water cycle extremes as requiring innovation and have also informed the PWR Report. Despite the significant challenges, there are promising directions emerging, including the realization that certain phenomena in some regions and seasons may provide greater skill to build upon, that key observing approaches have been proven, are ready and can simply be deployed, and that promising research directions in data assimilation, modeling and physics can be advanced, while more impactful means of delivering information can be employed.

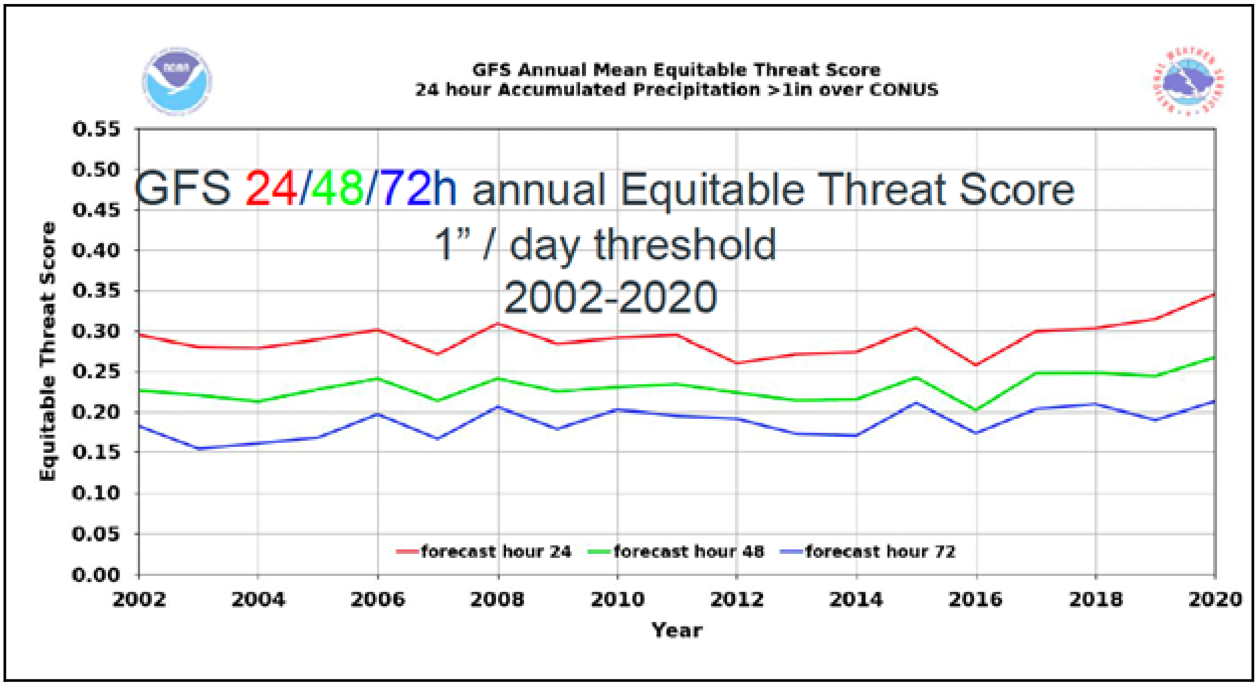

Figure 9: Global Forecast System (GFS) Annual Mean Equitable Threat Score. *This shows the slow evolution of precipitation forecast skill over the Continental United States (CONUS) in the GFS over the last 20 years. The equitable threat score is a metric that quantifies the skill of a forecast relative to random chance, with values ranging from 0 (no skill) to 1 (perfect skill). The 24-hour (red), 48-hour (green) and 72-hour (blue) forecasts all indicate minimal increases over this period.*[35]

First, gaps in observations and limitations in the ability to fully use them must be filled. These include fundamental gaps in measuring the weather, ocean, land and aerosol conditions that ultimately control clouds and precipitation formation, as well as measuring the precipitation itself, such as for flash flood warnings. NOAA's GPRA metrics can be expanded and refined to better represent prediction of the key phenomena that create extreme precipitation, as well as characteristics of the precipitation itself. Extreme precipitation and associated streamflow cannot be predicted without predicting the storms that produce them, and each storm type (tropical, thunderstorms, atmospheric rivers, winter storms) have their own challenges and opportunities for better measurement and prediction.

There are existing and potential new observations from ground, radar, aircraft, ocean, and satellite that can be more fully utilized through better data assimilation systems (OD-1, OD-2). New methods and capabilities in assimilation strategies can unleash even greater value from the existing and future observing systems (OD-3, OD-4), while advanced reanalysis methods (OD-5) are especially important for extreme event prediction because they can provide more and better representations of past extreme events to learn from and to train artificial intelligence tools. Fundamental gaps in observations of the boundary layers between land and atmosphere (OD-6), including moisture below the surface, and between ocean and atmosphere (OD-7), including of the heat content variations that are hidden below the ocean surface, are required to support both short-term (days to weeks) forecasts and especially sub-seasonal to seasonal (S2S) predictions. Precipitation ultimately forms from water vapor, whose horizontal movement occurs primarily in atmospheric rivers, for which errors in position, content and structure contribute greatly to errors in predicting the precipitation they fuel, and for which an integrated observing strategy has been demonstrated and can readily be expanded (OD-8). Finally, gaps in radar and satellite coverage can be filled through use of networks of smaller ground-based radars

(OD-9) and satellites (OD-10) that complement the backbone of big radars and satellites we depend upon.

Second, beyond critical improvements in Earth system models (FO-1), predicting water cycle extremes requires coordinated cross-organizational focus on water cycle metrics, community modeling, and data assimilation infrastructure in addition to enhanced coupling across critical interfaces, such as groundwater, vegetation, and coastal (FO-4, FO-7). The progress in hydrologic prediction in NOAA's National Water Model includes a vision for the use of different modeling approaches tailored to different regions. The importance of this cannot be overstated, as it represents a major new direction that sets NOAA up for success. Predicting water cycle extremes requires customized observations and weather forecasts to drive accurate streamflow and flood prediction, including coastal storm surges and associated coastal, estuarine and river flooding, as well as snowpack, evapotranspiration, and soil moisture in drought situations.

Third, major investments in improved information delivery are essential for realizing the benefits of improved prediction of water cycle extremes and impacts. For example, community modeling via open science (ID-1) and enhanced data integration and dissemination (ID-3) through hydrologic data assimilation and NOAA-wide coordination on water prediction are keys to success. Given the costly and deadly nature of floods and droughts, along with the disproportionate impacts on disadvantaged groups, critical analysis of social and behavioral aspects of water cycle impacts (ID-4) as well as more equitable information collection and delivery (ID-5) are needed.

5.5 Highly Reliable, Fully Accessible Weather Information

Modernizing weather information delivery is imperative to meet immediate operational data dissemination requirements, particularly during extreme events (ID-1 to ID-3, FO-6).[36] Modernizing weather information delivery is also essential for developing platforms for inclusive and open science that make information findable and accessible to all sectors and communities, and that supports collaborative research and citizen science. NOAA is a primary government source of environmental observations and forecasts but needs new hardware and software (including hybrid cloud strategies), and open science policies and practices to achieve integrated high reliability, full resolution weather data and information access and dissemination for the Weather Enterprise, across and beyond NOAA.

Box 4: Open Science
Open science is a goal to ensure the accessibility and usability of scholarly methodology, data, software, meetings, and publications. Open science refers to the entire scientific process. Open science is widely seen as normative in that science requires the communication and critical examination of results before they are accepted, and this social collaboration relies on transparency and honesty to assure the replicability and reproducibility of results.[37-39]

Inaccessible, siloed, and encumbered data and storage, including observations and full-resolution model output, and processing platforms, leads to underutilization, greatly reducing operational value, which limits scientific discovery, new product innovation, and societal benefits. Although new funding to complete previously planned work to address bottlenecks should help, data access and visualization software issues within the NWS (i.e., Advanced Weather Interactive Processing System (AWIPS) II and Satellite Broadcast Network (SBN)) continue to limit the effectiveness and efficiency of forecasters in and outside of the weather forecast offices. These immediate and ongoing operational requirements must be addressed in order to fully benefit from ongoing investments into weather research and forecasting (ID-2). Climate change and the extreme weather events that arise from climate change are grand challenges affecting all people, often disproportionately affecting the economically disadvantaged.[40] Environmental equity and justice will only be achieved with the full commitment, scientific expertise, and technology from all sectors. NOAA is uniquely qualified to lead in this effort and has initiated steps in this direction, such as the NOAA Big Data Program (BDP), but the persistence of the now-obsolete "download and process" model within NOAA perpetuates nonuniform access to information, which favors larger organizations.

There is a need for highly available and disaster-proof data access portals that are operationally supported (i.e., 24/7/365) to provide all NOAA weather and climate forecast and observational data in industry recognized formats. Scalable, maintainable, and sustainable portals would meet the needs of public and private partners and would address current gaps in, and obstacles to, the provision of consistent, reliable, secure data access and dissemination across NOAA and with enterprise stakeholders, for ingress and egress of data in the national interest. Outdated dissemination methods hinder sharing information with public (i.e., interagency) and private sector partners (e.g., aviation, shipping, roads, utilities) regarding hazards (e.g., severe, tropical, fire, winter, air quality, flooding). In particular, research focusing on fire weather and aviation would address related research and operational knowledge and data gaps, which are hampered by current data management and dissemination practices (ID-3).

Box 5: Aviation Weather

Providing aviation weather and volcanic ash information and forecasts are key NWS missions. NOAA needs to be able to ensure that all aviation weather data (including aircraft observations) and forecasts, are available to the aviation sector of the Weather Enterprise 24/7/365. This includes continuing to coordinate weather research funding and talent between NOAA, the Federal Aviation Administration (FAA), and the Department of Defense (DoD) and focusing on a single National Aviation Weather Research program that ensures data, forecasts, and information delivery to meet the needs of all aviation users. A very near-term issue for NOAA is to make its data available in a highly reliable manner and in full resolution. Currently the NOAA Aviation Weather Center is not able to do this and has no definitive plans or budget to make this happen, even though they have data that are used by every airline in the world in real-time to support safe and efficient airline operations.

NOAA Lockheed WP-3D Orion. Credit: NOAA/OMAO/AOC.

Democratizing science and data in the Weather Enterprise by investing in highly available operational portals and updated dissemination methods will result in NOAA weather data—including observations, forecasts, and historical data—being readily accessible to all parties, including academic researchers, industry consumers, NOAA line offices and other government entities, and citizens. This includes third-party and citizen and crowdsourced data that are supported in a shared commons or marketplace, and a shared commons or marketplace for aviation weather data and forecasts and specifically any available aircraft data and observations.

Democratizing science and data in the Weather Enterprise will foster multi-sector innovation through data and platforms that are open and broadly accessible in practice to everyone, with: open, uniform, flexible, preservable data formats and infrastructure; cloud platforms; Earth platforms; and business platforms.

Creating open science platforms is an essential element of this theme as well as an important outcome (ID-1). Open science opens up the scientific process from idea inception to result, including data, software, publications, and meetings. Open science platforms can: a) support diversity and inclusion, leading to improved diversity at NOAA as well as within the environmental science community in general; b) provide access to all communities, including traditionally underserved communities; and c) support a geographically distributed workforce (FE-8), broadening access to talent, and supporting an agile and effective workforce that can be mobilized during times of crisis.

6. Pillars that Enable a Weather-Ready Nation

Introduction

As noted in section 3.2, and illustrated in the PWR Strategic Framework (Figure 5), this report is organized around three principal pillars that represent NOAA's role in the development and delivery of weather information and its underlying foundational elements. Information flows through the three pillars - observations and data assimilation, forecasting, and information delivery - to support a Weather-Ready Nation (WRN), while the needs of a WRN provide feedback through the pillars as requirements. The three pillars and the findings and recommendations associated with each are discussed in this section.

6.1 Observations and Data Assimilation (OD)

The Observations and Data Assimilation Pillar is the first of the three pillars in the Priorities for Weather Research Strategic Framework – the framework that illustrates the foundational elements and process of NOAA's development and delivery of weather information. NOAA owns and operates a wide array of observing systems to support its mission. In addition, NOAA leverages environmental data from a variety of external sources to supplement its observing assets. These sources may include other federal agencies, industry, academic and international partners. Data assimilation is the technique that combines the incomplete observations with the short-range numerical model forecast to obtain an analysis that best represents the state of the weather (Figure 10).

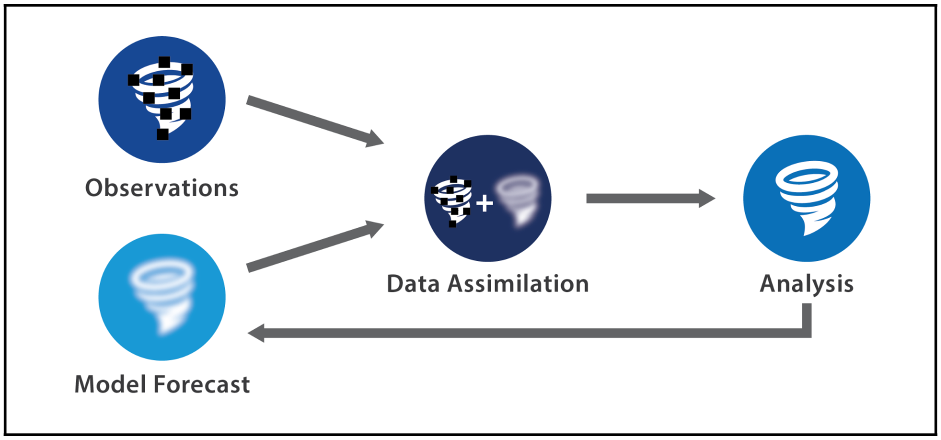

Figure 10: *Data assimilation is an objective process that fuses incomplete observations with short term numerical model forecasts to determine as accurately as possible what the true state is. The estimate of the true state is termed as "analysis," which can be used to initialize the next forecast.*

Data assimilation plays a critical role in addressing nearly all NOAA mission areas across all scales including improving numerical weather prediction, optimizing observation network design, producing analysis and reanalysis, and improving numerical models. Studies have shown that advancement of data assimilation can close the weather forecast skill gap between the United States and that of the world-leading operational numerical weather prediction centers. Figure 11 demonstrates that the NOAA Finite-Volume Cubed-Sphere Dynamical Core (FV3) model initialized from the European Centre for Medium-Range Weather Forecasts (ECMWF) initial condition (created by ECMWF modeling and data assimilation system) has similar forecast accuracy as that of the ECMWF forecast.

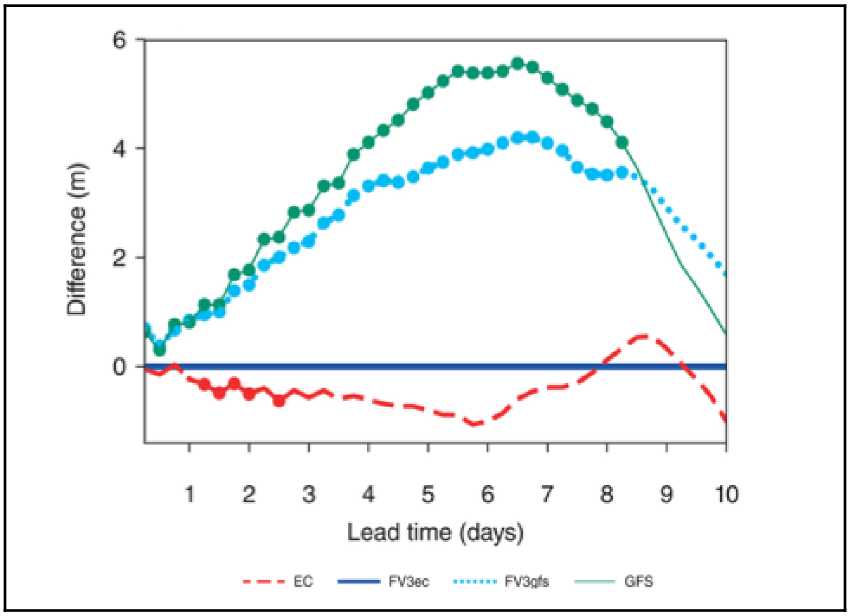

Figure 11: *Adapted from Magnusson et al. 2019.*[41] *Root Mean Square Errors differences for 500mb height forecasts for Northern Hemisphere. The differences are with respect to the NOAA FV3 model initialized from ECMWF initial condition (FV3ec, dark blue). EC (red), FV3gfs (cyan dashed) and GFS (green) denote respectively ECMWF forecast, NOAA FV3 model initialized from NOAA's own initial condition, and NOAA's legacy model. This figure demonstrates that the NOAA FV3 model initialized from the ECMWF initial condition has similar forecast accuracy as that of the ECMWF forecast*

The Observations and Data Assimilation Pillar presents a set of recommendations to advance the underlying science, Earth system monitoring and weather forecasting that supports the Nation's need for better weather information in many sectors. Observations and data assimilation requirements are highly dependent upon the space and time scale of the targeted phenomena and can range from very short lead times for rapidly developing phenomena to very long lead times, extending to multiple years for some slowly varying features. Sensors range from simple soil moisture probes to sophisticated radars and other remote sensors. Systems are ground based, or carried on buoys, drones, balloons, uncrewed systems, ships, aircraft or satellites to ensure observation of the atmosphere, land, cryosphere and ocean that are key to weather science and prediction. Observations over remote undersampled regions (especially aloft and offshore) are key to many types of forecasts and represent some of the remaining gaps addressed here.

These recommendations support weather science and prediction to meet NOAA's current mission requirements and GPRA goals, and identify new requirements that support decisions in key use areas. Some recommendations are to implement and expand the coverage and the assimilation of well-established observing technologies, while others describe the need for research and development of new sensors and new data assimilation methods. The readiness levels (RL) range from research (RL 1 to 2), to development (RL 3 to 5), to demonstration (RL 6 to 8), to deployment (RL 9).

The combined recommendations recognize that some specialized science and technical capabilities are required but are not well supported by NOAA and other agencies. Furthermore, workforce gaps are limiting progress, therefore approaches to fill them are recommended. Partnerships between NOAA and academic entities are key to catalyzing and sustaining innovation and workforce development. Such partnerships are also an effective approach to co-innovate and bring results into operations. Getting information to users and the public is enhanced through a Weather Enterprise approach involving the private sector. Strategic planning and implementation of computing resources are also recommended.

The analysis of the weather research requirements related to observations and data assimilation identified three priority areas:

- Use and assimilation of existing observations
- Advanced data assimilation methods, capabilities and workforce
- Observation gaps and use and assimilation of new observations

Each of these priority areas provides observation and data assimilation findings based on previous reports and on extensive input collected through the overall report development process and recommendations to advance the underlying Earth system science, analysis, and product development that NOAA needs to more fully realize the value of its forecast pipeline. Combined with recommendations from the "Forecasting" and "Information Delivery" Pillars they support the narrative themes of this report.[5]

Priority Area 1: Use and Assimilation of Existing Observations

The existing system of in situ and remote sensing observations consists of a wide range of measurement types, and platforms from which they are made, i.e., ground-based, balloon, aircraft, ships, ocean buoys,

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[5] Note that the focus of the Observation and Data Assimilation Pillar section is the acquisition and assimilation of Earth system data. The collection of social and human behavioral sciences data is covered in the Information Delivery section.

underwater systems, and satellites. Many observation systems were deployed to meet one requirement but can be useful in meeting others, however assimilation systems, models, and decision support systems were not necessarily designed to incorporate these multiple uses. Better integration of these data into multiple systems has potential to improve extreme event warnings, model forecasts and sub-seasonal to seasonal (S2S) predictions and outlooks.

OD-1 Recommendation: Maximize the use and assimilation of underutilized ground-based, airborne, and marine-based in situ, remote sensing, and crowd-sourced observations.
Observations are the foundation that supports the NOAA mission. Effective utilization of the existing observations is critical for accurate forecasts.

Findings:

1. Some NOAA systems have been found to have capabilities beyond those of the system's original design purposes and these capabilities could clearly benefit NOAA operations. Examples include ceilometers that were designed to measure cloud base, yet also can estimate boundary layer depth, and WSR-88D dual-polarization radars that were designed to improve rainfall estimation, yet the dual-polarization variables also may advance model microphysics representations and data assimilation.

2. Private sector instrumentation development and capabilities have expanded dramatically in the past decade: pressure data are available from smartphones; home weather stations are common; drones are increasingly being used for environmental monitoring; crowd-sourced weather applications allow users to report precipitation type and provide training to help with report accuracy. Significant investments by the private sector have resulted in many advanced technologies and systems. These systems include advanced polarized weather radars, automated aviation weather observations with artificial intelligence, in-cockpit aviation and marine weather displays, and satellite and mobile device weather dissemination. These private sector capabilities can complement federal systems, filling gaps and providing additional and more detailed local weather information.

Weather radar in Riverton, Wyoming. Credit: Kelly Allen, NWS

3. Little investment is made to assimilate the above ground-based observations into numerical weather prediction (NWP) models. This situation limits the value of the observations and reduces the return on investment.

4. Prediction of water cycle extremes (precipitation and streamflow) and their cascading impacts (e.g., drought, flood, wildfire, etc.) requires specialized observations and assimilation for atmospheric and hydrologic models, including the cryosphere. Measuring and assimilating measurements of the movement of water vapor in the atmosphere horizontally and vertically, which fuels precipitation, requires specialized approaches. The rapidly-expanding networks of soil moisture observations could help the National Water Model, by better recognizing when dry soils will reduce short-term runoff, or when saturated soils will increase risk of flooding. Snowpack measurements are vital to predicting snowmelt and new observations should be assimilated. The altitude above which precipitation falls as snow, i.e., the "snow level," is second only to precipitation amount in determining storm runoff in mountainous areas, and snow-level radars are now part of key mesonets.

Critical Actions for OD-1:

OD-1.1. Develop a clear, well-defined process to stay informed of how NOAA instruments and data are being used outside of NOAA and explore integration of new observation systems that have been or are being developed by the private sector and in academia. The goal is to identify how they could be used most advantageously to advance NOAA's mission, and to streamline testing, evaluation, data assimilation, and use in NOAA research and operations.

OD-1.2. Expand capabilities that provide support for testing observational strategies and capabilities from existing under-utilized ground-based observations identified above through funding collaborations between those who have developed or are developing the observational systems and those with expertise in data assimilation. Such effort will allow the observations to be assimilated most effectively in NWP.

OD-1.3. Develop a clear, well-defined process to select and fund new observations for NOAA operations and have these observations ready for use in data assimilation systems.

OD-1.4. Apply advanced and efficient data assimilation methods (see OD-3) for extreme precipitation prediction, icing, hydrologic and storm surge models, taking advantage of new networks of soil moisture, snowpack and snow level measurements, as well as novel airborne, ocean and satellite observations. Measuring forecast performance for extreme precipitation, streamflow and storm surge will help advance forecasts of these hazards. The next generation National Water Model (or system of regional models) is in development and could benefit from assimilation of these new observations now and in the future. Cost and benefit analysis should be performed to determine the optimal assimilation of such observations.

OD-2 Recommendation: Maximize the use and assimilation of underutilized satellite observations. United States leadership in delivering accurate weather forecasts for weather of all types requires assimilation of best available satellite observations to inform numerical models.

Findings:

1. Improving the assimilation of satellite observations in the operational NWP models can be realized through expanded collaboration between NOAA, the Joint Center for Satellite Data Assimilation (JCSDA), academia and other government agencies within the Unified Forecast System (UFS) framework.
2. Due to limited resources, the following satellite observations are significantly under-utilized in data assimilation: all sky radiances including those that sense clouds and precipitation, all surface radiances, and hyperspectral sounders.
3. Lack of understanding of observation errors and observation biases, and the large differences between model and observation all contribute to the under-utilization of satellite observations in the NWP model.


GOES satellite observing Earth. Credit: NOAA

4. Water-level observations using nadir data from current satellites can play a key role in monitoring and predicting coastal storm surge and inland flooding, including through assimilation in hybrid models that bridge coastal ocean, estuary and river conditions. Wide swath satellite water-level data could be of future value if the technology is possible.

Critical Actions for OD-2:

OD-2.1. Prioritize resources to expand collaboration between NOAA, JCSDA, academia and other government agencies to perform research and development of satellite data assimilation and its operational transition, with JEDI as the open source to enable such collaboration.

OD-2.2. Provide sustained support to improve fast radiative transfer models for all-sky and all-surface radiance data assimilation.

OD-2.3. Provide sustained support to investigate methods to effectively assimilate satellite observations into NWP models (i.e., estimate satellite observation error and bias), and to investigate efficient methods to evaluate satellite observation impacts (e.g. Observing System Simulation Experiment (OSSE), Forecast Sensitivity Observation Impact).

OD-2.4. Develop applications of novel satellite measurements for monitoring and prediction of coastal storm surge.

Priority Area 2: Advanced Data Assimilation Methods, Capabilities and Workforce

The potential exists to modernize, and even revolutionize, the assimilation of existing and new observations into weather, precipitation, hydrology and S2S prediction systems. This priority area recognizes and identifies promising directions to advance assimilation methods, including many sophisticated approaches for the atmosphere, ocean, and hydrosphere (lakes, streams, soils, glaciers), as well as to couple the assimilation of data across different zones where these Earth system elements literally touch one another (i.e., the ocean-atmosphere, land-atmosphere, and land-underground interfaces). One of the major limitations in pursuing these promising directions is the limitation in people technically prepared to work in this mathematically and computationally complex topic for which graduate education and a workforce development strategy are vital components.

OD-3 Recommendation: Significant new support for novel methodology research and workforce development for data assimilation is necessary to establish and maintain state-of-the-science capabilities.
Data assimilation plays a critical role in addressing nearly all NOAA mission areas across all scales. Advancement of data assimilation research and development at early readiness levels will help the United States advance world leadership in weather prediction and allow sustained workforce development to fill the severe workforce gap in data assimilation.

Findings:

1. Data assimilation plays a critical role in a) providing initial conditions for numerical predictions (Figure 12); b) producing analysis and reanalysis; c) optimizing observation network design; d) improving numerical models; and e) understanding system predictability, dynamics and processes.

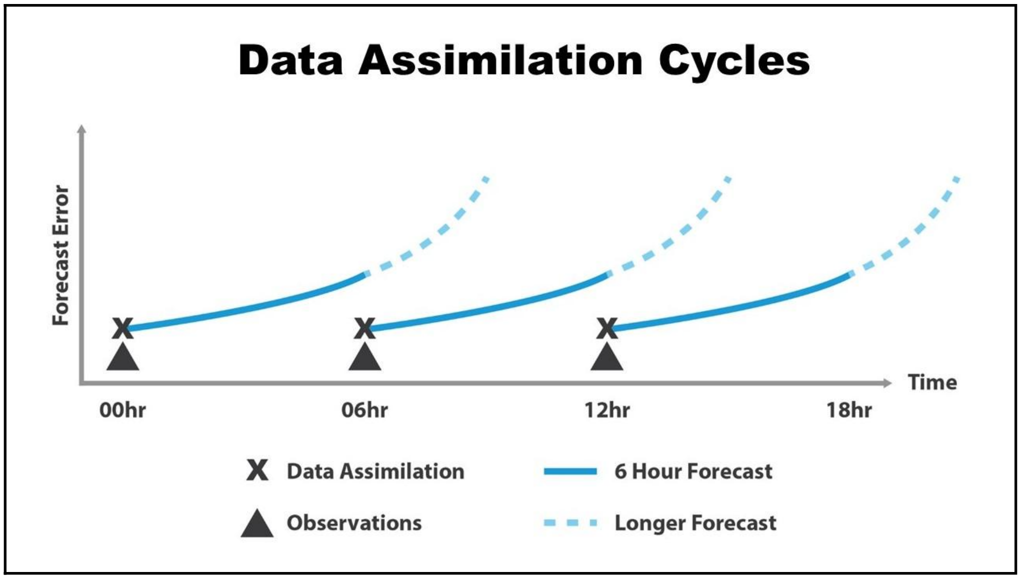


Figure 12: *Data assimilation combines the information from the observations and short term (e.g. 6-hour) forecast to produce an estimate of the current state of the atmosphere (termed as analysis), which is utilized to initialize the next forecast cycle. This process is repeated and cycled in operational numerical weather prediction.*

2. Advancement of model initial conditions through data assimilation is shown to be critical in significantly improving NWP. Studies by the European Centre for Medium-Range Weather Forecasts (ECMWF) show that the NOAA FV3GFS forecast model has similar forecast skills as the ECMWF model if FV3GFS is initialized by the ECMWF model initial conditions (Fig. 11).[41]

3. Data assimilation faces significant challenges associated with the future landscape of high-resolution, multiscale numerical models and a myriad of existing and new observations. Addressing these challenges will require innovative research and development in data assimilation.

4. Currently, the United States does not have an established mechanism to support innovative research in data assimilation.

5. It is well recognized by NOAA and other agencies that there is a serious lack of data assimilation expertise in the workforce. Data assimilation is inherently multi-disciplinary.

Critical Actions for OD-3:

OD-3.1. Establish a research program that is forward-looking and long-term (i.e., five years) to support innovative data assimilation methodology research across all spatial and temporal scales for weather and water, including the following eight topic areas:

- Novel use of artificial intelligence (AI) and machine learning (ML) in data assimilation
- Development of a multiscale data assimilation approach
- Development of data assimilation methods that account for nonlinearity and non-Gaussianity
- Development of methods to estimate observation errors and bias, and development of cost-effective and accurate observation operators
- Development of a scalable and efficient data assimilation algorithms and systems

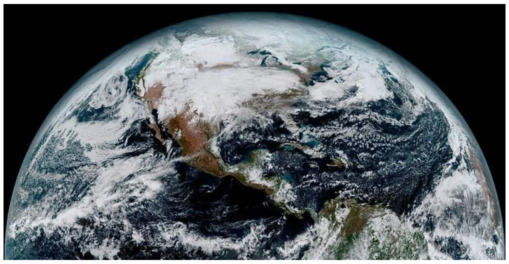
- Development of methods to represent or reduce numerical model error and bias using data assimilation
- Effective use of data assimilation to guide observation network design
- Creation of versatile data assimilation approaches for streamflow prediction using the National Water Model, and demonstration across a range of geographical and hydrological conditions

OD-3.2. Create a university consortium to address critical research challenges for data assimilation and to foster a growing data assimilation workforce. Goals of this consortium should include:

- Tackling critical research issues for data assimilation through innovative research
- Increasing significantly the number of graduate students, especially Ph.D. students, in data assimilation
- Utilizing the modern software, Joint Effort for Data assimilation Integration (JEDI), developed by JCSDA to conduct data assimilation research and development to facilitate research to operations (R2O)
- Collaborating with NOAA to prioritize critical research areas in data assimilation (operations to research)
- Enabling an effective collaboration infrastructure (universities, NOAA labs and centers, JCSDA)

OD-4 Recommendation: Advance coupled Earth system data assimilation for weather, water, and sub-seasonal to seasonal forecasting.
Earth system components are truly coupled in nature. Hence, NOAA's Earth system models should accurately emulate this coupling. The data assimilation system should also fully integrate all components of the Earth system (e.g., atmosphere, hydrosphere, ocean, cryosphere, land, aerosol, etc.). In other words, the observations in one Earth system component should influence the correction of other Earth components during the data assimilation for both short-term weather (e.g., hurricane, convection at continental United States, etc.) and S2S scale forecasts.

Findings:



Earth image captured in January 2017 by GOES-16 satellite. Credit: NOAA

1. The establishment of the fully and strongly coupled data assimilation system will effectively propagate information across the boundary layers among different Earth system components to improve the analyses of the individual components and the entire Earth system as a whole. This will lead to improved forecast skills from short-range weather to S2S timescales.
2. NOAA's operational NWP systems currently only have the capability for weakly coupled data assimilation. In other words, data assimilation is done separately for individual Earth system components and falls short of what can be achieved from a coupled data assimilation system.

Critical Actions for OD-4:

OD-4.1. Support the development of a workforce skilled in coupled data assimilation for weather, water, and S2S forecasting.

OD-4.2. Invest in research and development on the assimilation of observations of the Earth system boundaries. It is crucially important to identify, represent, and reduce model errors at the Earth system component interface in a data assimilation framework.

OD-4.3. Partnerships within NOAA, with other federal agencies ("the whole government"), universities and academia, private companies, and international operational centers should be established to make development of coupled data assimilation at all spatial and temporal scales a priority. JEDI is a unique framework for streamlining such collaboration and should be integral to this effort.

OD-4.4. Support physical process studies involving coupling between major Earth system components using coupled data assimilation as tools.

OD-4.5. Drastically reduce the data latency to improve operational coupled data assimilation.

OD-5 Recommendation: Advance the production of regional and global reanalyses.
Reanalyses (see Box 6 in Section 6.2) serve a large number of purposes, including long-term monitoring, detection and attribution of extreme events, forecast performance evaluation, improved use of observations, calibrating sub-seasonal to seasonal prediction, and development of numerical models and data assimilation methods. They are invaluable to both research and operations.

Findings:

1. While several international forecasting centers support robust reanalysis activities, a full Earth system reanalysis has not been produced by NOAA in more than a decade.

2. Advancement and production of reanalysis require large amounts of dedicated resources for observation data management; system updates including models, data assimilation and observations; and end-user services.

3. There are several important research challenges. The best value for the reanalysis research investment is obtained through linking the research and development of the reanalysis with the research and development of NWP model and data assimilation.

Critical Actions for OD-5:

OD-5.1. Invest in reanalysis as a user-driven operational production and service in support of Earth science research, NWP forecast product development, climate services, and private sector applications.

OD-5.2. Invest in research, with development and computing resources for global and regional reanalysis. Investments include improving input observations, leveraging and implementing NWP model and data assimilation research and development (FO-1, FO-2, OD-1 to OD-4), developing an optimal reanalysis configuration, and independent verification of the reanalysis. The service needs to rely on stable, dedicated resources including staff and HPC, but also leverage efforts from other agencies in the research and development and production of reanalysis.

OD-5.3. Develop a continuous and comprehensive high-quality, multi-decade reanalysis that supports the use of AI and ML for the development and study of environmental scenarios.

OD-5.4. Determine and establish an optimal life cycle for reanalysis that serves multiple purposes.

Priority Area 3: Observation Gaps and the Use and Assimilation of New Observations

Observations are the basis for weather predictions. Without accurate measurements of the basic weather conditions, and of the complex storm systems that develop and create hazards and benefits, modern weather prediction would not be possible. Meteorology, hydrology and oceanography have a long history of developing, deploying and using novel observing systems and a variety of platforms to get those systems to where the action is - in the sky, soil, rivers and oceans. In situ and remote sensing methods are ubiquitous and satellite systems provide remarkable global coverage. Nonetheless, serious observational gaps remain. Innovations are needed to fill those gaps, including hybrid approaches, such as measurement of rivers of water vapor in the sky that drive extreme precipitation. In some cases, new sensors need to be invented (i.e., for the atmosphere and ocean boundary layers), and new ways to deploy them are required (i.e., balloon, aircraft, surface and underwater platforms, small satellites). This priority area recommends a range of approaches that cover the needs for high-resolution local data for severe weather, to better measurements of the ocean supporting seasonal predictions.

OD-6 Recommendation: Develop and deploy a national boundary layer, soil moisture and smoke observing and data assimilation system for weather and sub-seasonal to seasonal prediction.

People live and work in the atmospheric boundary layer, and its characteristics exert a major influence on many weather phenomena ranging from thunderstorms to atmospheric rivers and overall seasonal weather patterns, and yet it is poorly observed. The requirement is to establish a national ground-based boundary layer, soil moisture, and smoke and aerosol observing system, with a vertical profiling network at its core. It supports research and prediction of processes within the lowest levels of the atmosphere, at the interfaces of the atmosphere with the underlying surfaces and in smoke and aerosol plumes.

Findings:

1. There is a long and sustained record of advocacy by the community for a national planetary boundary layer (PBL) observing network. Recent research studies and community national reports call out the importance of the PBL and highlight the need for improved PBL observations to advance forecast skills, in particular summer forecast skills. The need for temporally-continuous vertical profiling of PBL wind, temperature, and moisture is placed high on the list of observational needs and priorities for advancing weather prediction skill beyond seven day range.

2. The high priority observations also include the PBL height, and the air-surface (land, ocean, sea ice) exchange processes given the role of PBL as a key connector to other components of the Earth system. To advance prediction over longer time scales, and meet the needs of hydrological and ecosystem modeling, soil temperature and soil moisture observations are critically needed.

3. There are a number of existing observational profiling technologies and systems of moderate to high readiness level (RL) that can provide the needed measurements. These include a range of active (radars and light detection and ranging (LiDAR)) and passive (infrared and microwave) remote sensors, radiosondes and dropsondes, and even some of the current NOAA underutilized systems, such as ceilometers. A number of emergent technologies and new observational systems for PBL profiling at lower RLs are being advanced by the research community and by the private sector.

4. To advance weather prediction over a range of time scales, from beyond ten days to S2S range, requires a comprehensive set of PBL observations, together with the ability to assimilate these data into numerical weather prediction models.

5. Many wildfires with extensive smoke plumes have affected much of the Nation in recent years. These plumes can change ground and surface temperatures dramatically, with additional impacts on prediction and surface air quality. Major gaps in observations exist, including the amount of smoke and aerosol (including dust) emitted, the chemical and related characteristics of the smoke and aerosols, and the downstream altitude and dispersion of wildfire smoke plumes.

Smoke plume over northwestern US in September 2020. Credit: European Space Agency (contains modified 2020 Copernicus Sentinel data, processed by ESA)

Critical Actions for OD-6:

OD-6.1. Develop a coordinated national profiling network over land with an offshore extension to routinely collect observations within the lower troposphere, observing the atmosphere from the ground up. Continuous profiling at high temporal frequency and vertical resolution is dictated by dominant temporal and spatial scales of processes within the PBL. To close the extant PBL observational gap, the proposed NOAA ground-based PBL observing network should be complemented by satellite, surface-based, and airborne measurements in a hybrid observing system.

OD-6.2. Support collaborations between those designing and implementing the ground-based PBL system and those involved in data assimilation. The objective of these collaborations would be two-fold: to use data assimilation experiments to advance the design of the network, and to ensure that new observations can be assimilated immediately after the observational system testing and evaluation has concluded.

OD-6.3. Support partnerships between NOAA, and the academic and private sectors, to design and implement such a national network and will help advance the NOAA mission.

OD-6.4. Develop and deploy ground-based remote sensors that measure smoke plume insertion altitudes and its down-mixing and deposition to the surface and assimilate the data into numerical models. Develop and deploy airborne sensor packages to measure vertical profiles of smoke and aerosol concentrations and chemical makeup, by leveraging existing weather sensor and communication capabilities on commercial aircraft and their inherent ascent and descent flight patterns. Assimilate these observations into numerical models to improve wildfire prediction.

OD-7 Recommendation: Observe the ocean, its surface boundary layer, and ocean-atmosphere feedbacks, on weather space and time scales for seamless Earth system data assimilation and forecasting from minutes to years.

The ocean has been underutilized as a source of predictability, particularly for the coastal regions where a large fraction of the population is concentrated. Combined oceanic and atmospheric boundary layer observations will increase understanding of the fundamental physics of the air-sea interactions required for an Earth systems approach. NOAA is an international leader in integrated ocean observations for science and operations. Combining that leadership with advanced Earth system models (FO-1) that include ocean forecasting capabilities, coupled data assimilation (OD-4), and development of a skilled workforce at multiple degree levels (FE-9), will enable U.S. leadership as a pathway for delivering accurate weather forecasts (Section 5.2) for high-impact weather (FO-6), water cycle extremes (OD-8, FO-4), and comprehensive coastal applications (FO-7).

Findings:

1. There is an emerging consensus that Earth system models coupling atmosphere, ocean, land, freshwater, and ice will increase prediction skill, particularly for forecasts beyond a few days. The ocean supplies ~90 percent of moisture to Earth's hydrological cycle and the upper three meters of the ocean have more heat capacity than the entire atmosphere. Ocean-atmosphere feedback influences weather from minutes (e.g., sea breezes to atmospheric rivers and hurricanes) to interannual timescales (i.e., El Niño/La Niña Southern Oscillation (ENSO) and climate).

2. Earth system models require accurate exchanges of heat, mass, and momentum between components, which requires accurate observations and modeling of the boundary layers. The PBL over land and the air-sea transition zone are consensus targets for enhanced observations, modeling, and advanced data assimilation methods.

3. Ocean-atmosphere feedbacks are turbulent and complicated and are not well understood, particularly at space- and timescales relevant to weather, due to lack of direct observations of turbulent exchanges and their coupling with the boundary layer processes. Better fluxes will improve coupled forecasts of the Earth system from minutes to years, especially extreme precipitation and flooding that disproportionately impact underserved communities.

4. Data-assimilative ocean models have long demonstrated the value of integrated approaches to ocean observing. Mapping of surface conditions can combine satellite and shore-based (e.g., high frequency (HF) radar) remote sensing, surface and sub-surface sampling with moored, drifting, or rapidly-advancing Uncrewed Systems (UxS). Observing System Experiments (OSE) and Observing System Simulation Experiments (OSSE)[42] can contribute to the network design.

5. Despite being recognized for their operational maturity by the Global Ocean Observing System (GOOS) as existing (e.g., Argo, Global Drifter Program, tropical mooring arrays) or emerging (e.g., OceanGliders, HF radar) observing system elements, several of these systems are still incomplete or aging in critical global or U.S. coastal waters. The polar regions are especially poorly observed, despite their influence on weather.

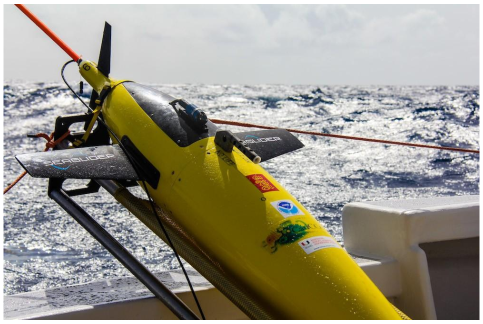
6. The United States is a world leader in ocean observations. NOAA benefits from a flowering of public and private innovations in uncrewed and remote sampling systems, but most ocean data

are not used for weather forecasting. NOAA is uniquely suited to bring together community experience in observations with modeling and forecasting of the ocean, land, and atmosphere, to coordinate across agencies, and to transform U.S. operational weather forecasts through an Earth system approach.

7. Observing the ocean and its Earth system interactions are well suited to a partnership approach within NOAA, with other federal agencies, universities and academia, and private companies, both nationally and internationally. These interactions encourage innovation in observation systems, data assimilation and analysis, forecasts, and communication. The distributed nature of ocean observing systems, and the diversity of data streams, prompt the need for a geographically distributed workforce with a wide variety of technical skills.

Critical Actions for OD-7:

OD-7.1. Complete, maintain and integrate existing ocean observing networks, and enhance existing ocean observing platforms with additional sensors (e.g., biogeochemical, salinity, currents, etc), to improve Earth system model forecasts and provide an integrated context for enhanced ocean boundary layer observations.


Underwater hurricane glider. Credit: NOAA

OD-7.2. Leverage the expanding capabilities of the full community to design and build a nested ocean boundary layer observing system that can resolve the air-sea fluxes and inputs to their parameterizations to improve understanding and forecasts. Deploy instruments to measure the ocean and atmosphere transition layers and their covariances on weather space and timescales and analyze them with data-assimilating coupled models. Evaluate the forecast skill and evolve the observing system to maximize efficiency once the coupled models and data assimilation are sufficiently validated. Deploy an observing system that can maintain improved forecast skill.

OD-7.3. Link these recommended major components for the ocean mixed layer to the atmospheric boundary layer recommendation. One focal point is the coastal regions, where a) the marine and continental layers meet and interact, b) the uncertainties in weather forecasting are particularly emphasized, and c) where weather events impact large human populations, marine ecosystems, marine transportation and offshore energy infrastructures. The system should also be linked with biogeochemical observations for managing ecosystems and forecasting coupled events such as harmful algal blooms in oceans and lakes.

OD-8 Recommendation: Leverage and expand atmospheric river (AR) observations to improve flood and drought prediction and to enable forecast-informed reservoir operations.
Water and emergency managers often cope with too much or too little water and require better information on storms that produce extreme precipitation. However, precipitation prediction skill has not improved substantially in the last 20 years. The multi-agency, OSTP-led Earth System Prediction Roadmap (2020) identified expanded research, observations and communication needed to better anticipate and mitigate water cycle extremes and their cascading impacts, including atmospheric river type storms.[34]

Findings

1. NOAA has articulated the need for improved precipitation forecasts in the form of a Grand Challenge developed jointly with the Department of Energy (DOE). It highlights very slow gains in precipitation forecast skill over the past two decades. A key recommendation from this report, which incorporated substantial community input, was to focus on predicting the storm types that are most responsible for extreme precipitation.[43]

2. The United States Army Corps of Engineers (USACE)-led Forecast-Informed Reservoir Operations pilot studies have identified atmospheric river (AR) storms as the leading cause of extreme precipitation and flooding in the west (84% of all flood damages in the western United States are due to atmospheric river storms, based on forty years of FEMA data[44]); Major impacts across other key U.S. regions also occur. The Fourth National Climate Assessment added ARs as a fourth type of extreme storm to track as the Earth's climate changes[45].

3. Improved skill in predicting rainfall, and this storm type in particular, would enable more flexible reservoir operations, which can mitigate drought and flood impacts. The more skillful the AR forecast, the more flexibility there can be to hold water after a storm, or to release it ahead of a storm. This expands the potential usefulness of existing dams to create greater resilience to the increasing swings between drought and flood that is already being seen, simultaneously supporting the economy, public safety and the environment.

4. A pilot program to improve predictions of ARs and their extreme precipitation and impacts ("AR Recon") recently demonstrated success. It used aircraft (Figure 13), additional buoy data and airborne radio occultation (from GPS satellites), combined with novel data assimilation techniques. An initial operational capability has been established as a Research And Operations Partnership (RAOP) between universities, NWS, OMAO, the United States Air Force and others. Profound gaps in current weather observations have been found that AR Recon fills, and improvements in prediction skill at one to four days lead time has been demonstrated[46-50].

Critical Actions for OD-8:

OD-8.1. Implement a multi-phase program to improve the understanding and forecasting of ARs that leverages current and future aircraft, buoy, and satellite capabilities. The program should build upon existing capabilities and programs to expand coverage in space and time and improve forecasts through advanced data assimilation (OD-3), as well as integration of ocean surface and mixed layer observations (OD-7).

OD-8.2. Adopt a research and operations partnership approach, including engagement of the international and academic communities.

OD-8.3. The program development and implementation should create new forecast skill metrics targeting extreme precipitation prediction in the west and the phenomenon, ARs, that produces it. It should target socio-economic impact considerations including for use in reservoir operations to mitigate drought and flood impacts.

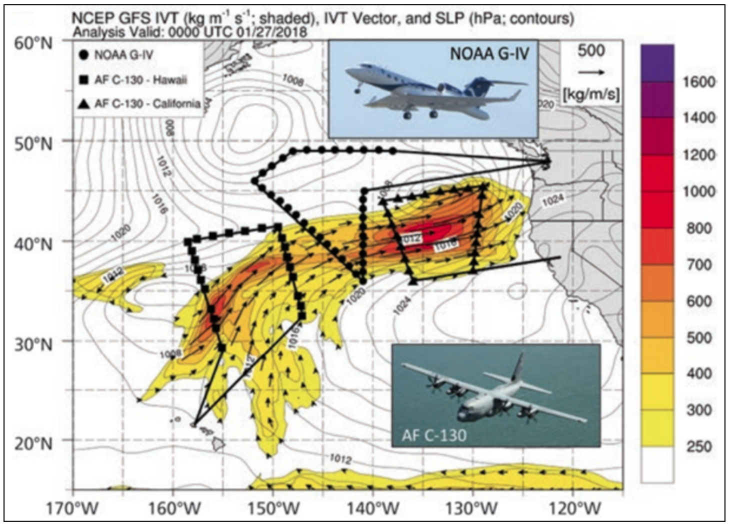


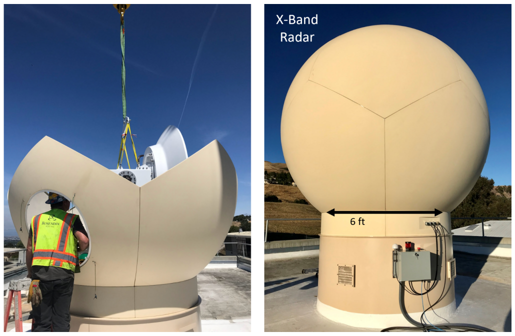
Figure 13: *Example of Atmospheric River Reconnaissance case that used three-aircraft (two from U.S. Air Force and one from NOAA) to measure a strong atmospheric river (orange/red object; color scale is integrated water vapor transport kg/m s) as it approaches the U.S. west coast where details of AR intensity, location and duration largely determine where extreme precipitation and potential flooding will occur.[51] These data fill a distinct gap in satellite and other standard observations and are assimilated by NOAA's leading global model, the GFS.*

OD-9 Recommendation: Fill radar gaps using diverse weather radars and data assimilation.
Deploy and integrate smaller, cheaper scanning radars into NOAA's current network of very large radars, roughly doubling the number of radars, to better detect significant precipitation and severe weather over more of the Nation and more equitably across the population, starting immediately.

Findings:

1. Currently NOAA ground-based radar observations have a significant limitation in the lower part of the atmosphere due to Earth's curvature and terrain blockage. Seventy percent of the western United States below one kilometer altitude above ground is unobserved and key gaps in coverage in the eastern United States are inordinately where under-represented groups live and work.

2. Regional networks of small, relatively inexpensive, commercially available radars (C-band and X-band) have seen wide application worldwide and the United States needs to catch up.



X-band scanning radar used in the Advanced Quantitative Precipitation Information (AQPI) demonstration of a gap-filling radar network in a mountainous, urban area. Credit: Cooperative Institute for Research in Atmosphere.

3. The larger, more expensive S-band radars used by NWS as the backbone of national radar coverage are a core capability; remaining gaps can be filled by smaller radars.

4. Although some regions have the benefit of special radar coverage, primarily through television stations, there are limitations with long-term reliability and equitability of coverage.

Critical Actions for OD-9:

OD-9.1. NOAA should develop a clear, well-defined process to integrate more fully data from existing radars operated by others to complement NOAA ground based radars.

OD-9.2. NOAA should begin deploying commercially available, low-cost C-band and X-band radars into areas in the western United States where NEXRAD gaps are most significant, and in the eastern United States where environmental justice analysis has found poor coverage from existing radars, with at least thirty radars deployed within three years.

OD-10 Recommendation: Prioritize smallsat/cubesat observation and data assimilation.
NOAA observations have been based on large satellites that are reliable, capable, impactful, yet expensive with a long development cycle. Recently, substantial and rapid progress has been made in smallsat/cubesat technology. This provides a great opportunity for NOAA to define the role of smallsats/cubesats in its observing system; i.e., for gap mitigation, faster technology refreshment, more frequent revisit opportunities; complementing large satellites in temporal and spatial coverages; opening up new ventures with the private sector.

Findings:

1. Compared with large satellites, the costs of smallsats (including cubesats) and their launching service are much lower, their development cycle is much shorter, and mission operation and ground system costs are usually lower and available commercially. While the lifespan of smallsats may be two to five years, they can be replaced regularly, partly because of substantially reduced launching costs. However, they may require innovative propulsion and altitude control , and they need to address pointing, longevity, capacity, and calibration and validation issues.

2. Most smallsat payloads are not ready for operational use at NOAA and hence investments are needed. The assimilation of their data is also a challenge. In general, smallsats are unlikely to replace large satellites; instead, they may complement and strengthen the current NOAA observing system to form a hybrid satellite architecture.

3. Smallsats also represent a paradigm shift for the development of data assimilation systems. For “big bus” instruments, a subject matter expert would work on it for years and hand pick channels, bias correction predictors, thinning length scale, observations error variance, etc. For smallsats, more agile data assimilation systems need to be built where observing systems can come in and out (semi-) automatically.

4. NOAA's 2018 comprehensive architecture study of nearly 100 prototype constellations concluded that small and medium size satellites, ride shares and hosted payloads are a high-value frontier area.

Critical Actions for OD-10:

OD-10.1. Develop robust smallsat/cubesat technology demonstrations.

OD-10.2. Establish a capability to develop, test and implement new data assimilation methods tailored to using smallsat/cubesat measurements (e.g., via collaboration with the academic community).

Observation and Data Assimilation Recommendations Outcomes:
There is an absolute connection between forecast skill and the quality, number and location of observations collected and used in predictive systems from decision support tools for severe weather to models predicting storms in the coming days and weeks, and statistical methods extending to months and seasons. Advances in observations, and their assimilation into numerical models, combined with rapid increases in computing capacity and modern information delivery systems are the foundation of the Weather Enterprise. They underpin much of today's modern world, and the gaps that remain contribute to the loss of untold lives, property and livelihoods, and in the most catastrophic cases even whole communities. The actions and programs described above, taken together over the next decade, can transform, even revolutionize, weather, water and S2S predictions and their associated uses. They represent a robust and diverse set of approaches to sometimes simple and other times vexing technical challenges. It can be as simple as investing more in well-established solutions, or it may require exploring and inventing creative new approaches by capitalizing on the Nation's remarkable capabilities in government, academia and the private sector, and fostering mutually beneficial partnerships across these sectors. Specific outcomes include:

- 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 timeliness 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 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."

6.2 Forecasting (FO)

NOAA provides weather, water, and climate forecasts and warnings for the United States, its territories, adjacent waters and ocean areas, for the protection of life and property and the enhancement of the national economy. The ultimate goal is to have a society that is prepared for, responds to, and is resilient to weather, water and climate events. The NWS collects and analyzes more than 6.3 billion observations per day and releases about 1.5 million forecasts and 50,000 warnings each year. Forecasters build their forecasts with observations that feed numerical weather, water and climate models whose output is analyzed using individual scientific expertise. Forecasters communicate this information and potential impacts to the public, emergency managers, and other core partners to help make decisions that save lives and protect property. NWS forecasts, warnings, and data and products form a national information database and infrastructure used by other governmental agencies, the private sector, the public, and the global community that enables core partners to make decisions when weather, water or climate has a direct impact on the protection of lives and livelihoods.

Yet, despite huge assets in environmental prediction, including the largest associated research community in the world, an open data policy, and a robust private sector weather industry, forecasting skill from the hourly to two-year time scales lags that of the best available within the international community. Foundational research investments in Earth system modeling (including reanalyses and reforecasts), and in high-impact weather, water cycle, air quality, fire weather, and coastal modeling, have the potential to enable rapid progress toward world leadership in operational numerical prediction, leading to the best possible products and services delivered to all users of weather information.

The analysis of the weather research requirements related to forecasting identified two priority areas:

- Foundational Earth system modeling
- Advancing critical forecasting applications

Examination of these two priority areas led to the development of seven recommendations (FO-1 to FO-7) that address needs and gaps in current forecast modeling capabilities. Accompanying each recommendation are findings based on the study's extensive information gathering process, and supported by 27 critical actions that identify the key steps needed to achieve the seven recommendations.

Priority Area 1: Foundational Earth System Modeling.

The vision of NOAA's Unified Forecast System (UFS)[52] is "to continuously improve world-class predictions of weather and climate to assure the protection of life and property and the advancement of prosperity." To achieve this vision, NOAA is simplifying its production suite, so that its energy can be concentrated on just a few modeling systems, the backbone for which should be an Earth system model (ESM) used for global forecasts at time scales of one day to two years. While the current Global Forecast System (GFS) has a sophisticated atmospheric model, it is not fully (two-way) coupled to the oceans, sea ice, surface hydrology and other parts of the Earth system, which research has shown can affect short- and long-term weather forecasts. Moreover, NOAA's current Climate Forecast System (CFS) has not been updated since 2010, leaving it considerably behind in capabilities of other global modeling centers, which update their systems every 4 to 6 years. Recommendations for addressing these challenges are contained in FO-1 to FO-3 below.

FO-1 Recommendation: Accelerate Earth system model development and seamless prediction.
NOAA's mission - to understand and predict changes in climate, weather, oceans, and coastal environment - covers the entire Earth system, requiring predictive capabilities for the key processes within, and interactions among, the components of the Earth system. To provide societally relevant forecasts, spanning weather to climate time scales from global to local spatial scales, a seamless and fully coupled modeling framework that provides a holistic treatment of the Earth system is essential.

Findings:

1. Improvement in weather-climate modeling requires a comprehensive treatment of the Earth system components that are relevant on weather and climate time scales - atmosphere, oceans, land surface, biosphere, cryosphere, hydrologic cycle - and interactions between these components, which is termed an Earth system model (ESM) (see Box 2 in Section 5.2). The UFS, under development by a NOAA-led community of researchers, provides a framework for ESM development.

2. There are salient aspects of the coupling among Earth system components and how to characterize uncertainty that are not fully understood, and research is required to advance the knowledge and ability to model their interactions. There is an urgent need for a clear long-term mission around which NOAA labs, external researchers, and operational centers should be unified.

3. Mesoscale-resolving ESMs, run in ensemble mode to estimate uncertainty, are needed for many high priority forecasting problems. Interactions among Earth system components at mesoscales (three to twenty kilometers) are fundamentally different from large-scale interactions. For example, the local correlation between sea surface temperature and surface wind speed over the ocean is weak and largely negative at large scales but strong and positive at mesoscales. This means that the large scale wind variability is stirring the upper ocean to cool it, while the mesoscale ocean temperature variability is altering the static stability of the atmosphere near the surface. Therefore, mesoscale interactions must be accurately represented in ESMs in order to predict mesoscale features such as thunderstorms, ocean eddies, polynyas, etc.

4. Improvements in observations, particularly of fluxes of energy, mass and momentum between Earth system components during extreme conditions, and advances in coupled data assimilation and the physics of intra-component interactions are essential. Ensembles of ESM forecasts are required to assess forecast skill, quantify forecast uncertainty, and take best advantage of observations to initialize and evaluate and validate forecasts.

5. Biogeochemistry (BGC) observations and forecasts are the next frontier - exploring the carbon, nitrogen and other cycles that current models struggle to represent accurately. ESMs should model accurately BGC cycles of carbon and nitrogen that affect weather and climate, because stakeholders require forecast products that depend on BGC processes.

Critical Actions for FO-1:

FO-1.1. As ESMs mature, modeling for prediction at lead times of hours to years should move toward ESMs, with model-prognostic components for all Earth components, including the atmosphere (including aerosols), land surface, oceans, and sea ice, that are coupled for both data assimilation and forecasting (see Box 2 in Section 5.2). That is, the current GFS and planned seasonal forecast system (SFS) should advance to become full ESMs.

FO-1.2. Focus Earth system model development on appropriate and consistent performance metrics that align with stakeholder needs.

FO-1.3. Facilitate research to operations (R2O) for seamless prediction by adopting a unified ESM, including accurate BGC cycles of carbon and nitrogen, with coupled data assimilation, ensemble, and downscaling refinement capabilities for all forecasting applications.

FO-1.4. Mesoscale-resolving ESMs (less than five kilometer grid spacing in all components) should be developed and implemented into operations by 2030, with subgrid-scale uncertainty represented by machine-learning-based stochastic parameterizations.

FO-1.5. An open development framework should be employed, including data assimilation, initialization, forecast, post-processing and statistical modeling. Investments should be made to enable ESMs to take advantage of the rapidly changing high performance computing architecture and software engineering advances (see FE-7).

FO-2 Recommendation: Achieve the best possible operational numerical weather prediction at all time scales.

Accurate and actionable weather forecasts are the foundation of society's ability to be resilient to weather and to leverage weather for the improvement of life and economy. This includes using forecasts for everything from planning daily activities to preparing for major weather disasters. However, weather forecasts are not perfect, nor optimally used, and hence the Nation continues to be vulnerable to the adverse effects of weather. Further, the Nation faces increasing vulnerabilities associated with a changing climate, which extends its exposure to impactful weather. Numerical weather prediction (NWP) is foundational for weather forecasting and NOAA's NWP and forecast products are foundational to the Weather Enterprise. NWP models encapsulate our understanding of weather; effective use of their products is critical to further improving the Nation's resilience to weather.

Findings:

1. Weather forecasts have dramatically improved over the past fifty years. Advancements in NWP capabilities are the foundation of these improvements owing to upgraded models, increased observations, enhanced data assimilation and new computing technologies.

2. Despite having the largest weather research and development enterprise in the world, the United States does not have the world's best operational global NWP capabilities. Hence, the nation is less resilient, less secure and more vulnerable to the impacts of weather.

3. There are numerous reasons why the United States does not have the world's best NWP capabilities, including a fractured research and development enterprise with broad interests and motives not always focused on operational NWP improvements, insufficient computing resources, difficulties in filling new technical positions with qualified candidates, and an overly complex modeling portfolio. NOAA's adoption of the UFS is a promising foundation to improve the nation's NWP capabilities, but alone it is insufficient.

Critical Actions for FO-2:

FO-2.1. Having the best possible operational NWP is foundational to meeting the overall NOAA mission and maximizing the nation's resilience to adverse weather and a changing climate. To achieve this, it is recommended that NOAA commits to creating the best possible operational NWP within a framework that includes:

- A realistic, yet aggressive strategic plan and program focused on this objective that includes explicit metrics, activities, investments, and milestones.
- A process by which Congress and the Nation routinely assess and hold NOAA accountable to execute those plans and achieve their goals.
- Significant new research investments in the entire spectrum of science needed for world-class operational NWP, including coupled Earth-system science and modeling, model physics, data assimilation, ensembling, post-processing and AI technologies, all under the framework of the UFS.
- Initiatives such as the Earth Prediction Innovation Center (EPIC) that support and incentivize external partners to conduct NWP modeling research and development in a manner that contributes to the NWP excellence goal.

FO-2.2. Acquire substantially more computing power to support the research, development, testing and implementation of a world class NWP portfolio (see FE-6). A majority of the new computer resources should be allocated to research and development within NOAA and across the broader weather research community.

FO-2.3. In conjunction with other relevant federal agencies such as the National Science Foundation (NSF), catalyze a substantial increase in the pipeline of next-generation researchers, technicians, and practitioners trained to advance the requisite and complex modeling, observation, assimilation, and computing science and technology. This could be accomplished by enhancing and catalyzing institutions, programs and other initiatives that can teach these disciplines. NOAA should make dedicated modeling, data and computing platforms available to support such programs.

FO-3 Recommendation: Establish a regular, sustained Earth system reforecasting activity to enable a more effective cadence of operational model improvements.

Regularly produced global reanalyses and reforecasts are critically important components of operational prediction systems and provide the basis for long-term monitoring, detection and attribution of extreme events, model bias correction, and weather modeling and forecasting research.

Box 6: Reanalyses and Reforecasts

Reanalyses are gridded multi-decadal datasets generated by a fixed data assimilation system and numerical model. They are done retrospectively, using up to thirty to fifty years of past observations, yielding a temporally homogeneous gridded data set. See OD-5 for recommendations on reanalyses. Reforecasts, initialized from reanalyses, are multi-decadal, retrospectively-generated forecasts using a fixed forecast system. They are an essential component of an operational ensemble prediction system and are necessary to calibrate real-time forecasts, with particular value at longer lead times when useful forecast information may be obscured by model bias. Reforecasts are also valuable for: predictability research; identifying and correcting the sources of model biases; and as important training data sets for the development of machine learning algorithms.

Findings:

1. The demand for reforecasts is growing, particularly for hydrology and water resources and S2S prediction. While several international forecasting centers support robust and periodic reanalysis activities, a full Earth system reanalysis has not been done by NOAA in more than a decade.

2. Reforecasts are under-resourced by NOAA. Reforecasts require considerable computational resources and staff with specialized experience. Under-resourced reforecasts can delay operational model implementation.

3. There are several important research challenges, which include: a) balancing requirements for assessing the predictability of rare, extreme events versus removing mean bias; b) the optimal cadence and configuration for reanalyses, reforecasts and operational implementations, including resolution and ensemble size; and c) applying new discoveries in observation-informed treatment of model error.

4. Regular Earth system reforecasting would enable: a) more effective planning and execution of major forecasting system changes; b) acceleration of the model development cycle, particularly for longer lead forecast guidance, and c) more effective use of ML algorithms.

Critical Actions for FO-3:

FO-3.1. Invest in reforecasting as a user-driven operational production and service in support of Earth science research, NWP forecast product development, and private sector applications.

FO-3.2. Invest in research and development to advance reforecasting.

FO-3.3. Determine the optimal configuration and cadence of reanalysis, reforecasting and operational implementations that can provide the best framework for model development and climate monitoring.

Priority Area 2: Advancing Critical Forecasting Applications

Most of the loss of life and property associated with weather comes from extreme events (see Section 5.3), many of which occur at scales of one to ten kilometers. The ESM recommended above cannot resolve all of these extreme phenomena, leading to the need for a suite of high-resolution models that can accurately predict severe thunderstorms, wildfire spread, hurricanes, winter weather, river flooding, storm surge, etc. Many but not all of these models can be based on the backbone ESM, adapted for regional scales and with appropriate physics. The findings and recommendations in this section (FO-4 to FO-7) identify gaps and possible solutions to the challenge of providing more accurate and actionable guidance for extreme weather events.

FO-4 Recommendation: Enhance prediction of Earth's water cycle extremes to achieve integrated water cycle modeling.

NOAA plays a unique and vital role in predicting water cycle extremes, including floods and droughts, that supports hazard mitigation, water supply, transportation, agriculture, fisheries and innumerable users of water cycle information. Droughts and floods are both deadly and costly weather and climate disasters, with costs of $6.4 billion and $3.8 billion per year, respectively.[31] A key Weather-Ready Nation (WRN) objective is to "Deliver actionable water resources information from national to street-level and across all time scales; provide minutes-to-months river forecasts that quantify both atmospheric and hydrologic uncertainty; improve forecasts of total water in the coastal zone by linking terrestrial and coastal models in partnership with the National Ocean Service; and deliver forecasts of flood inundation linked with other geospatial information to inform life-saving decisions."

Findings:

1. The predictability of the water cycle is one of the most important challenges related to understanding the impacts of climate change, as articulated in the OSTP Fast-Track Action Committee (FTAC) on Predictability report.[34] However, there are major gaps in our ability to understand and predict the water cycle, from precipitation to evaporation, floods to droughts, and forecasting both water quantity and quality. For example, over the last twenty years, there has been little improvement in precipitation forecast skill for high-impact weather events.[35]

2. Water cycle research and operational water cycle prediction involves technical and management capabilities spread across several disciplines (e.g., meteorology, hydrology, oceanography, coastal sciences) and line offices (NWS, OAR, NOS, NESDIS, OMAO). Some of the challenges in advancing the associated science, observations, models, predictions and products in the water prediction arena is a result of this complexity. Disconnects exist and this complexity requires deeper coordination and stronger partnerships. For example, flood forecasting within NWS National Water Center (NWC) is undergoing a major transition, and would benefit

A flooded intersection in Baton Rouge, Louisiana on August 14, 2016. Credit: Louisiana Department of Transportation and Development.

from added connections with National Centers for Environmental Prediction (NCEP), Climate Prediction Center (CPC), Weather Program Office (OAR), coastal and eEstuary expertise (NOS), Satellite Observations (NESDIS) and National Integrated Drought Information System (NIDIS).

3. The water cycle is closely coupled with the energy and carbon cycles, in addition to human behavior and related socioeconomic drivers (i.e., food-water-energy nexus).

Critical Actions for FO-4:

FO-4.1. Elevate the evaluation of water-cycle related variables including: precipitation analysis and forecasting; flood discharge and inundation; drought intensity, duration, and area; and water quality.

FO-4.2. Improve coordination among the multitude of intersecting efforts that set research priorities and correspondingly fund research related to the water cycle.

FO-4.3. Use a scientifically-vetted, supported, community water modeling framework and data assimilation systems in operational forecasting of water quality and quantity. Require benchmarking of forecast models with an open, transparent approach that supports code contributions and testing within two weeks.

FO-4.4. Make major, sustained investment in water data assimilation capabilities to accelerate the use of more water observation information and improve forecast product skill.

FO-4.5. Expand research to address scientific issues and uncertainties in model process coupling (i.e., compound flooding such as coastal-riverine-pluvial flooding, surface-groundwater coupling, land-atmosphere coupling). Model coupling is not just a software issue but is a significant science challenge.

FO-5 Recommendation: Substantially increase the level of effort to advance predictive capabilities for fire weather and air quality.
Air quality (AQ) and fire weather forecasts have high societal and economic value in preventing or mitigating disease and mortality. Climate change and rising frequency of compound hazards, such as heat waves in conjunction with drought or poor AQ, are driving increased importance of and reliance on these forecasts that are critical for decision support for evacuations, power shutoffs, public health advisories, and other incident responses.

Findings:

1. Operational AQ forecast requirements, recommended in 2004 for providing finer resolution and longer-term predictions, remain unmet[53].

2. Challenges include: a) the computational burden imposed by high-resolution simulations and by nonlinear gas-phase and aerosol emissions and chemistry; b) the need for two-way coupling with the surface to properly represent emissions and feedback; and c) the need for data assimilation of multiple

Smoke from Caldor Fire in September 2021. Credit: California Office of Emergency Services.

chemical species to capture variability of emissions on shorter time scales.

3. Similar challenges for coupling to the land surface and for representing emissions apply to the fire weather forecasts that are issued by the NWS. Very high-resolution (hundreds of meters) models and incorporation of fire feedbacks are needed to represent the extreme fire behavior that often represents the greatest threat to life and property.

Critical Actions for FO-5:

FO-5.1. Develop a comprehensive, coupled, ensemble-based Earth system model capable of hourly to seasonal prediction of atmospheric composition and AQ. The Earth system approach is fundamental to improved AQ forecasts, supplying accurate boundary conditions and initializations and the necessary coupling to land and water surfaces.

FO-5.2. Advance the use of ML to realize model efficiencies and thereby facilitate high-resolution and ensemble approaches needed to produce forecasts at the required spatial scales.

FO-5.3. Leverage and support interagency partnerships in model development and evaluation. This includes expansion of interagency cooperation via sharing of updated emissions inventories and codes and co-development of schemes for data assimilation.

FO-5.4. Provide additional computational resources for AQ and fire weather model research, development, and evaluation. The computational demands are large but are justified by the importance of these applications in protecting people and property and the need to accelerate progress.

FO-6 Recommendation: Commit to improving forecasts of high-impact weather through multi-sector partnerships, in concert with the Earth Prediction Innovation Center program.

High-impact weather (HIW) includes severe thunderstorms (tornadoes, hail, lightning, downbursts), hurricanes (high winds, storm surge and inundation), flooding, blizzards, cold and heat waves, ice storms, fire weather and severe pollution events. In addition to the 800 storm-related deaths per year from HIW noted in Section 5.3, there are roughly 700-1,300 heat-related fatalities per year[54], while premature deaths from poor air quality may total as many as 200,000[55]. More accurate and timely forecasts of HIW are key to mitigating risk from these events, thus saving lives and property. Achieving this goal requires that NOAA, through the UFS and EPIC, effectively coordinate model improvement efforts, both internally and with external partners. It should be noted that the NWS has other Mission Service Areas that address phenomena not covered in this report, such as space weather and tsunamis. They are characterized as extreme events that are infrequent but have high impact. For example, a large coronal mass injection could disable global power grids, GPS-based systems and other satellite communications. The December 2004 tsunami caused over 200,000 deaths along Indian Ocean coasts. The NWS has engaged in multiple partnerships with other agencies to monitor, predict and warn for these events.

Findings:

1. Challenges to be met and gaps to overcome to improve U.S. capabilities in forecasting HIW events include:

    a. Improved physical understanding, brought about by field experiments, process and predictability studies, which inform model physical parameterizations and conceptual models.
    b. Enhanced observational capabilities, especially in the planetary boundary layer (PBL), that resolve the phenomena to be predicted.

2. High-resolution, regional models, with sub-kilometer horizontal resolution, an appropriate dynamic core, and efficient data assimilation algorithms, are needed for hurricanes and other events dominated by convection. These models are nested in the UFS global model, which will become the ESM recommended in FO-1.

3. Research is needed on how best to create diverse and well-calibrated ensembles to enable reliable probability forecasts. Research needs to be done in both the data assimilation and forecasting components.

4. New diagnostic and post-processing products, aided by data mining and other AI and ML tools, are needed to communicate actionable guidance.

5. HPC resources are insufficient to meet even today's requirements given the high perishability (rapid refresh) of the forecasts, the high-resolution grid spacing, the volume of radar, satellite and other data to be processed, the sophisticated data assimilation schemes, and the large number of ensembles needed (see Section 7.2).

Critical Actions for FO-6:
Enhancing NOAA capabilities in high-impact weather forecasting will require NOAA to:

FO-6.1. Take a comprehensive approach to improving understanding and conceptual models of HIW phenomena.

FO-6.2. Work with partners within the UFS framework to develop sophisticated regional and nested models with enhanced model physics to increase their predictive skill in the ESM suite, and to improve techniques for ensemble generation and their applications to HIW events. As the ESM matures, there should be a careful assessment of whether separate stand-alone hurricane and water models add value to the production suite, with awareness of how ESM output is used by the community in other modeling systems.

F0-6.3. Make the NWS Warn-on-Forecast (WoF) vision (see Box 3 in Section 5.3) a high priority and extend it to other HIW phenomena in concert with the Forecasting a Continuum of Environmental Threats (FACET) program.

FO-6.4. Work with forecasters and social, behavioral, and economic scientists on innovative diagnostic and guidance products and effective communication of risks and impacts.

FO-6.5. Involve the external community via the EPIC program and extramural funding opportunities. NOAA should proactively ensure the success of EPIC by encouraging coordination and collaboration among all its relevant programs (e.g., Environmental Modeling Center (EMC), Weather Program Office (WPO), Office of Science and Technology Integration (OSTI), Developmental Testbed Center (DTC) and relevant OAR laboratories and Cooperative Institutes) with EPIC and the Weather Enterprise.

FO-7 Recommendation: Advance research on coastal processes in Earth system models to achieve comprehensive coastal modeling.

The coastal zone supports diverse uses, stakeholders and concerns, including approximately forty percent of the U.S. population; navigation and commercial shipping; alternative energy; pollutant tracking and cleanup; water quality; fisheries; recreation; and search and rescue. It is a critical component of the Blue Economy. At the same time it affects and is subject to some of the most energetic weather on the planet. Forecast modeling provides critical decision support information that protects lives and property and promotes the safe and efficient use of this environmentally treasured and economically vital area. The need for enhanced decision support is increasing as economic growth, migration patterns and climate change bring more people into this increasingly multi-use and hazardous portion of the Earth. An Earth system modeling approach is vital, as this is where atmosphere, ocean, land and watersheds converge and interact.

Findings:

1. The demand for forecasts of the coastal ocean, from physical to biological processes, weather to climate time scales, and street to national spatial scales, is growing for operational uses, ecosystem management, hazard assessment, warnings, response, and mitigation.
2. NOAA's responsibility for meeting these demands has evolved over time, is contained in at least five legislative actions, is spread across multiple line offices, and has resulted in the adoption of different models and different modeling philosophies.
3. A single coastal forecast model may not meet all NOAA users' needs; developing standards and best practices for coastal modeling is critical for reconciling differing modeling approaches and philosophies that currently exist across NOAA offices. Advancing coastal models will require coordinated investment in relevant Earth system science (ESS), model development (MD), data collection (DC), data science (DS), and HPC.

Container ships in the Port of Oakland. Credit: NOAA.

Critical Actions for FO-7:

Important challenges exist in individual model components, model coupling, and the integration of models and observations through data assimilation and adaptive sampling. Overcoming these challenges will require NOAA to:

FO-7.1. Support the following important areas for coastal modeling research: a) total water level, including the effects of ocean currents and structure, tides, surge, waves and overtopping, and fluvial and pluvial water sources to benefit decisions related to flooding and other weather-related hazards in the coastal zone, (contributions needed in ESS, MD, DC) and b) nearshore processes, particularly morphological modeling, air-sea-wave coupling, and physical-biogeochemical coupling to benefit decisions concerning weather-related hazards and water quality, including harmful algal blooms.

FO-7.2. Support research needed to make models more useful for forecasting including: a) model performance optimization for new computational platforms (contributions needed in MD, HPC); b) ensemble and probabilistic modeling with error metrics (contributions needed in ESS, DS); c) the expanded use of explainable AI and ML (contributions needed in ESS, MD, and DS).

Forecasting Recommendations Outcomes:

The investments into the forecasting pipeline focused on core model development and implementation (FO-1 to FO-3) and advancing critical forecasting applications (FO-4 to FO-7) will deliver unprecedented accuracy and value to the Nation's forecasts. They will increase innovation, with the potential to enable international leadership in forecasting. They will support a WRN by increasing forecast reliability and accessibility, and by enhancing public safety and resilience. They will result in foundational NOAA modeling capabilities by creating and providing:

- 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.
- A publicly-released strategic plan, with clear milestones and metrics, to have the world's best possible operational numerical weather prediction at all time scales.
- Routine reanalysis and reforecasts in NOAA's forecast production pipeline that provide historical context and advance critical downstream forecasting applications.
- Actionable water resource, river flow, and flood inundation information from national to street-level and across all time scales that quantifies both atmospheric and hydrologic uncertainty to inform life-saving decisions.
- Hourly to seasonal prediction of atmospheric composition and air quality that facilitates high-resolution ensemble forecasts that leverage and support interagency partnerships in model development and evaluation.
- Accurate, street-level, timely, and actionable forecasts of HIW including severe thunderstorms (tornadoes, hail, lightning, downbursts), hurricanes, flooding, blizzards, cold and heat waves, and ice storms.
- Comprehensive forecasts of total water in the coastal zone as well as nearshore processes from linked terrestrial and coastal models to support navigation and commercial shipping; alternative energy; pollutant tracking and cleanup; water quality; fisheries; recreation; and search and rescue.

6.3 Information Delivery (ID)

Information Delivery is the third pillar in the *Priorities for Weather Research Strategic Framework.* To reduce the impact of extreme weather, water, and climate events, NOAA is transforming the way that people receive and act on life- and property-saving information, with better forecasts, more accurate and timely warnings, and clearer communications, through programs such as FACETs, impact-based decision support services (IDSS), and Hazard Services. NOAA now provides information that helps emergency managers, first responders, government officials, businesses and the public make fast, smart decisions to save lives and property and enhance livelihoods. To continue and accelerate this transformation NOAA needs an integrated framework for weather information delivery that coordinates and integrates the suite of information delivery-related challenges currently being tackled in a profusion of ways across the agency.

The Information Delivery recommendations are intended to equip NOAA with the necessary workforce, infrastructure, organizational structure, and research activities to support its strategic priorities for weather information delivery. These are currently insufficient. This framework should infuse AI and cloud technologies into operational capabilities. It should also assimilate social and behavioral data from users, and assess and anticipate key user needs, including a focus on historically underserved and vulnerable populations. Ultimately this framework should create and deliver responsive weather data and guidance products, in a virtuous, iterative cycle. This will require embracing hiring and training partnerships and processes to support state-of-the-art weather research on these topics and creating a weather information delivery research program in collaboration with other agencies.

Analysis of the weather research requirements related to information delivery identified two priority areas:

- Highly reliable, high-resolution (HR2) weather information dissemination, with inclusive and open science to maximize societal benefits
- Promoting an ongoing virtuous cycle of collecting social, behavioral, and interdisciplinary observations, and assimilating and analyzing the data to improve weather information delivery

Each of these priority areas synthesizes extensive input from subject matter experts to support the resulting consensus recommendations to advance information delivery. Combined with recommendations from the Observation and Data Assimilation and Forecasting Pillars they support the narrative themes of this report. NOAA has commenced efforts in these priority areas in some instances that have not been fully funded; for example, the agency is short on necessary resources for computing and hiring scientific staff, and relying on nearly exhausted hurricane supplemental funds to maintain and support important programs such as the Hurricane Forecast Improvement Program (HFIP). Addressing these needs is critical, and in many instances urgent.

Priority Area 1: Highly Reliable, High-resolution (HR2) Weather Information Dissemination, with Inclusive and Open Science to Maximize Societal Benefits

There is an urgent need to modernize weather information delivery, both to meet immediate operational data dissemination requirements, particularly during extreme events, as well as to either leverage existing open source solutions or develop platforms for inclusive and open science that deliver information uniformly to all sectors and support collaborative research and citizen science.[37-38] NOAA is the primary nationally recognized government source of environmental observations and forecasts. Inaccessible, siloed, encumbered data and platforms hinder innovation, leading to underutilization, limiting scientific discovery, new product innovation, and societal benefits. For weather research efforts to be useful, immediate and ongoing operational requirements must be addressed.

Climate change and the extreme weather events that arise from climate change affect everyone, and disproportionately affect those who are economically disadvantaged or marginalized, for example due to racism and poverty. Environmental justice and leadership in this area will require an “all hands on deck” approach to draw upon scientific expertise and technology across the Weather Enterprise. NOAA is uniquely qualified to lead this effort, but it has traditionally relied on an obsolete “download and process” model that results in nonuniform access to information, favoring larger organizations and consortiums. Initiatives like the Big Data Program (BDP) are steps in the right direction but need further development. Modern, public, hybrid cloud platforms can be used to address multiple concerns—including robust and scalable data dissemination, information delivery to all communities, open science and citizen science that empower communities—and support the development of a skilled workforce. Open science platforms are an essential element of these recommendations, as they: a) support diversity and inclusion, leading to improved diversity at NOAA as well as within the environmental science community in general; b) provide uniform access to all communities, including traditionally underserved communities; and c) support a geographically-distributed workforce, broadening access to talent, and supporting an agile and effective workforce that can be mobilized during times of crisis.

ID-1 Recommendation: Embrace open science.
To support this recommendation, develop and maintain highly available, disaster-proof, operationally (24/7/365) supported, scalable data access portals, within two years; and fund an open science consortium to coordinate activities in response to the 2021 draft United Nations Educational, Scientific, and Cultural Organization (UNESCO) Recommendations on Open Science.

Findings:

1. The Weather Enterprise requires weather data, including observations, forecasts, and historical data that are uniformly and readily accessible to all parties, including academic researchers, industry consumers, NOAA line offices, other government entities, and citizens. This includes third-party and citizen and crowdsourced data supported in a shared commons and marketplace, and a shared commons or marketplace for aviation weather data and forecasts, specifically aircraft data and observations.

2. NOAA should lead the democratization of the Weather Enterprise to foster multi-sector innovation by ensuring data and platforms are open and broadly accessible in practice to everyone, with: open, uniform, flexible, preservable data formats and infrastructure; cloud platforms; Earth platforms; and business platforms.

3. Research is needed on:
    - Data representations that maximize preservability and FAIR (findable, accessible, interpretable, and reusable) principles
    - Ensuring equitable access to environmental data and information for all populations
    - Developing strategies that achieve long-term and uniform data storage and compute platforms for public and private entities with funding and service level agreements (SLA) in place
    - Data archeology for obscure or old data
    - Methods for provenance and trust for all NOAA-provided data

Critical Actions for ID-1:

ID-1.1. Develop and maintain highly available and disaster-proof data-access portals that are operationally supported (i.e., 24/7/365) to provide all NOAA weather and climate forecast and observational data in industry-recognized formats (e.g., Network Common Data Form (NetCDF), GeoJSON, etc.).

- These operational portals should be scalable and maintainable to meet the needs of public and private partners, completed within two years, and continuing for the next ten years.

- Data availability should be structured such that users subscribe for access to published information.
- Should include SLA and establish long-term contracts with explicit requirements and strong guarantees for operational information delivery, and second-tier SLAs for archived, historical, and research data that have reduced requirements.

ID-1.2. Create an open science consortium that includes private commercial and nonprofit partners, academia, and the open science community to coordinate activities in response to the 2021 draft UNESCO Recommendations on Open Science[56] and recent National Academies reports.[37-38] This consortium should a) normalize open science for the next generation of scientists that will participate in NOAA's Weather Enterprise, b) accelerate science by motivating and supporting the science community's move towards open science, and c) broaden participation in NOAA's Weather Enterprise and reduce barriers (see Section 7.3). This could include, for example:

- In collaboration with the broader weather community, establish consistent and open data standards to support open science; simple, general, cloud-optimized data formats and Application Programming Interfaces (API) that support accessibility, usability, and preservability throughout the Weather Enterprise, and simplify R2O
- Partner with other agencies (i.e., National Aeronautics and Space Administration (NASA), United States Space Force (USSF), FAA, United States Forest Service (USFS), United States Geological Survey (USGS)) to collocate data with high joint utility and to support a transition to cloud architectures
- Partner with other community science groups, working to preserve and protect our natural resources
- Build the community by creating summer schools, internships, conferences around open science, citizen science, and environmental justice
- Create open information tools for searching and analyzing data and publications, and tracking origin, provenance, and trust
- Develop methods for the deployment of algorithms, i.e., new methods for reanalysis, or new algorithms for processing large data sets (e.g., multi-radar multi-sensor (MRMS) data) {See Recommendation OD-3}

ID-2 Recommendation: Within two years, implement the existing plan to address NWS operational data dissemination challenges by leveraging content delivery networks and accelerating the migration to commercial cloud networks, as described in the Environmental Information Services Working Group (EISWG) report,[36] Recommendations 3 and 4. Prioritize retention of expertise in software, data, and networking within NOAA and NOAA contractors to address limitations and ensure future innovation.

Findings:

1. Data access and visualization software issues within the NWS (i.e., AWIPS II and Satellite Broadcast Network (SBN)) continue to limit the effectiveness and efficiency of forecasters in and outside of the Weather Forecast Offices and necessitate other free and proprietary software and websites to be utilized to successfully fulfill the mission.

2. In addition to affecting essential operations, data access and dissemination issues hinder implementation of new tools and technologies.

Critical Actions for ID-2:

ID-2.1. Leverage content delivery networks and accelerate migration to the cloud.

ID-2.2. Prioritize retention of expertise in software, data, and networking within NOAA and NOAA contractors to address limitations and ensure future innovation.

ID-3 Recommendation: Create a NOAA-wide function to provide Weather Enterprise data integration and dissemination strategy and operational oversight to ensure preparedness and response, within five years. This function should plan, monitor, and respond to issues to ensure consistent, reliable, secure data access and dissemination across NOAA and with enterprise stakeholders for ingress and egress of data in the national interest.

Findings

1. NOAA can provide leadership in the establishment of open platforms, but this is not an activity isolated to NOAA, nor a product delivered to an "external" community. It will require active engagement with multiple partners, including the open source and scientific community, cloud providers, as well as academic and private partners.
2. There are significant research and operational knowledge and data gaps in fire weather and aviation that require coordination within NOAA and across partner agencies.

Critical Actions for ID-3:

ID-3.1. Create robust coordination and collaboration frameworks that ensure effective dissemination and sharing of pertinent NOAA data, including addressing outdated dissemination methods, to the public sector (i.e., interagency) and private sector partners. These frameworks should address all sectors (e.g., aviation, shipping, roads, utilities, etc.) and hazards (e.g., severe, tropical, fire, winter, air quality, flooding, etc.).

ID-3.2. Research should be undertaken to understand the full extent of NOAA data utilization, especially across federal agencies and large commerce sectors, to better design and establish these frameworks.

ID-3.3. Ensure that there is coordination across agencies and partners (e.g., NOAA, FAA, DoD, universities, etc.) to eliminate duplication of efforts and maximize research talent and funding.

ID-3.4. Prioritize research and frameworks focusing on fire weather and aviation within NOAA and across partner agencies, the private sector, and universities to address significant research and operational knowledge and data gaps.

Priority Area 2: Promote an Ongoing Virtuous Cycle of Collecting Social, Behavioral, and Interdisciplinary Observations, and Assimilating and Analyzing the Data to Improve Weather information Delivery

Recent NOAA research efforts to improve the quality and usefulness of weather information and decision support highlight the potential for NOAA to become a global leader in convergent research that directly informs weather information delivery. The complexity of weather information delivery in rapidly changing information ecosystems together with the increasing urgency of extreme environmental event management and communication needs make a shift in NOAA's approach imperative. Opportunistic data collection from grant-funded social science research efforts are filling gaps but are not sufficient to enable NOAA to meet its broader weather information delivery goals.[20] The recommendations in this priority area recognize the laudable efforts by NOAA to prioritize and incorporate social and behavioral sciences into its external partnerships, its own leadership decision making, and its research endeavors. But the recommendations also highlight the need for additional resources and for further transformation of nascent information delivery research programs to develop and provide needed information that is accurate, timely, and usable. It is recommended that specific, strategic, high-priority research be conducted as part of a user-oriented weather information development and delivery research program that strengthens university-private-government partnerships and networks in order to provide agile prototyping and evaluation of products derived from extensive data on decision-making and behavior (Figure 14). To achieve its goals, NOAA will need to considerably strengthen its efforts to coordinate and support weather information delivery research in a holistic approach that cuts across hazards and engages the full diversity of user groups—including groups who originate and disseminate weather information (i.e., public and private sector forecasters) and other decision-makers (e.g., emergency managers, fire managers, underserved communities, Spanish-speaking and multilingual communities, individuals in diverse circumstances, volunteers in emergencies, etc.). Inclusive design principles - thinking about the most marginalized user groups first - will improve others' contingent experiences and make all user experiences more robust.

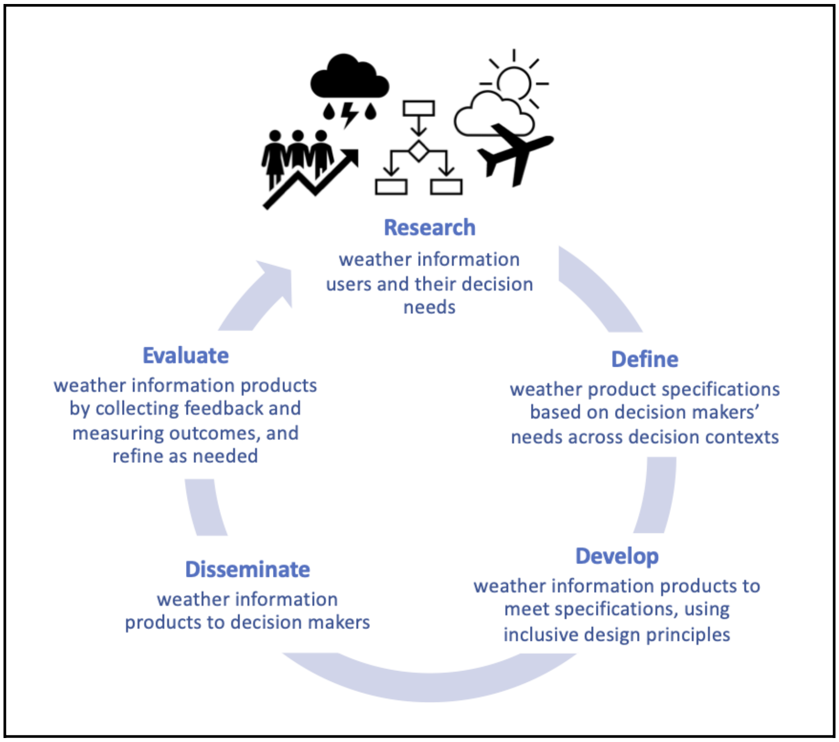


Figure 14: *A weather information development, dissemination, and evaluation research cycle that starts with decision makers and their needs (Information Delivery, Priority Area 2), in the broader context of observational, data assimilation, forecasting, and information dissemination weather research.*

ID-4 Recommendation: **Prioritize and integrate inter- and trans-disciplinary research on equitable and effective use of hazardous weather information**—including both deterministic and probabilistic information—for risk assessment and protective decision-making, including at individual, group, and community levels. Utilize multiple research methods whose results can be compared, contrasted, and cross-referenced.

Findings:

1. NOAA requires a new paradigm in which evidence about users' needs and barriers informs and drives the development and delivery of weather information and atmospheric research, conceptually, structurally, and culturally. This new paradigm would enhance development and delivery of user-oriented timely, meaningful, skillful (accurate), usable, and actionable weather information, with enterprise-wide systems and structures to advance, expedite, and regularly evaluate the development and delivery of user-oriented information.

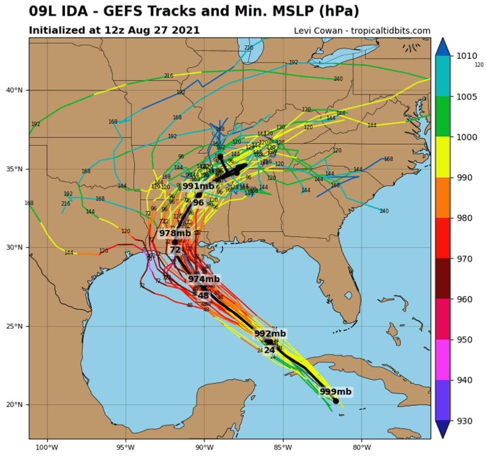
2. The equity assessment required of NOAA under Section 5 of Executive Order 13985[6] revealed service gaps and a mission critical need for NWS to systematically and intentionally engage the historically underserved and socially vulnerable communities that it serves, in order to meet the mission of NWS.

3. NOAA requires enhanced research, development, and evaluation efforts pertaining to access, interpretation, and use of forecast and other risk information (i.e., about impacts, efficacy and other protective measures) for different user groups and across diverse weather hazards, in order to provide information that is evidence-based and user-oriented.

Critical Actions for ID-4:

ID-4.1. Examine for whom, in what hazard scenarios, when, and how forecast uncertainty (probabilistic) information is advantageous versus when it is not, including whether and when it's potentially detrimental. Consider characterization, communication, and use of both forecast uncertainty and forecast confidence. Prioritize research on hazard scenarios exacerbated by climate change (e.g., fire weather, drought, heat, extreme precipitation and flooding, winter storms).

ID-4.2. Examine how to more effectively convey information visually, in a geospatial context (e.g., interaction modes, geographic contents, resolution, symbols and color selections, and semiotic principles), with a focus on how representations of the weather hazard (including uncertainty and scenario-based forecasts) combined with other information (e.g., infrastructure, landmarks, locations of supplies or shelters) can improve risk assessment and decision-making.



Track forecasts out to seven days for Ida from the 12Z (8 a.m. EDT) Friday, August 27, run of the GFS ensemble model (GEFS). Most models converged to predict a Louisiana landfall as a major hurricane, but confidence in track prediction decreases once over land.

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[6] Advancing Racial Equity and Support for Underserved Communities through the Federal Government, Jan 20, 2021. This service assessment is in progress but was reported in a briefing to PWR on August 4, 2021.

ID-4.3. Characterize and address issues of weather information inequity. Consider community-centered approaches to situate the research in particular cultures, populations, and resources. Research should include studying: a) information access (e.g., for non-English-speaking, deaf, people with hearing loss, visually impaired, etc.), b) geographic areas with poor infrastructural (cellular, internet, radar) coverage), c) protective response options (i.e., shelters, and time-to-reach them for those in manufactured housing), and d) potential mediators and/or moderators of these, such as social support and trust.

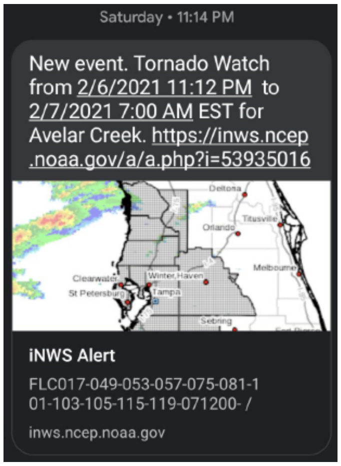
ID-4.4. Identify the circumstances (e.g., hazard type, region, season, etc.) in which automated guidance, including NWP-based guidance (deterministic, ensemble, and "blended" guidance) and AI- and ML-based guidance, does and does not work. Such research should consider hazard predictability limitations, trust in the guidance by users (including forecasters and end-users), NWS partners' IDSS needs, and failure implications.

ID-4.5. Conduct research on characterizing and communicating impacts of weather hazards, leveraging diverse data sources (e.g., traffic, retail purchases, infrastructure data layers, social media data) and potential AI and ML techniques. Such research must consider the predictability and prediction capabilities of impacts across scales and contexts. Conduct research to consider and clarify the capabilities of NOAA to communicate these impacts—perhaps depending on the type and scenario of the hazard (e.g., feasibility for rapidly-evolving weather hazards, like tornadoes, flash floods, wildfires)—versus in partnership with other public agencies (e.g., emergency personnel) and the private sector (see ID-6).

ID-5 Recommendation: **In collaboration with researchers working on Recommendation ID-4, NOAA should partner with other agencies and the private sector to develop, test, and evaluate probabilistic and deterministic hazard information delivery capabilities for a broad spectrum of end-users**.

Findings:

1. Communicating uncertainties has the potential to increase trust and better inform decision making and protective action under some circumstances. However, the demands for probabilistic products, and the contextual and other limits to their benefits are not well understood. The high bandwidth that probabilistic hazard products can require, both of computers and of human decision makers, may make them less useful than deterministic hazard products in some situations.



Saturday • 11:14 PM

New event. Tornado Watch from 2/6/2021 11:12 PM to 2/7/2021 7:00 AM EST for Avelar Creek. https://inws.ncep.noaa.gov/a/a.php?i=53935016

iNWS Alert

FLC017-049-053-057-075-081-101-103-105-115-119-071200- /

inws.ncep.noaa.gov

Example of iNWS Alert via text message. Credit: NOAA

Critical Actions for ID-5:

ID-5.1. Expand and strengthen relationships across academic, private and government sectors to allow rapid information exchange between research results and dissemination strategies to ensure that the most useful products have viable dissemination pathways.

ID-5.2. Coordinate organizational and geographical collaborations of NWS offices and centers with partner agencies, in social-functional networks, to optimize weather information flows through partner agencies' operational procedures. Social-functional network research could help formalize core aspects of IDSS, including their implementation through InteractiveNWS (iNWS), Integrated Realtime Impact Services (IRIS), and the IDSS management system (IMS) to enhance the value of and go beyond personal connections across agencies, increase mutual awareness of weather information availability and use, and promote preserving and sharing knowledge and experiences. This will require addressing Recommendations ID-1 and ID-2 above, to address capacity issues.

Recommendation ID-6: **Build capacity to develop multi-dimensional metrics, data repositories, and new data collection methods and standards for "baseline" data (i.e., not event-specific) and for event-specific "perishable" social and behavioral data**, particularly perishable data in the predictive phase of a threat as well as in the aftermath. These data should be quantitative and qualitative, and should include collection and analysis of data from conventional research instruments (e.g., surveys, interviews, participant observations) and less conventional data types and data sources (e.g., social media, citizen science and crowdsourced databases, mobile apps and smartphones). They should include, for example, geospatial metadata (on temporal and spatial scalar characteristics) from Did-You-Feel-It[57] type immediate post-event cross-sectional data collection, to data from experiments, to longitudinal data on weather information usage patterns within and across events and event-type.

Findings:

1. There is a need for both more systematic "baseline" (i.e., not event-specific) and event-specific "perishable" social and behavioral data, including data on weather information use, individual and collective decision making, and protective and responsive actions by individuals, organizations, and communities. Collecting data in the predictive and aftermath phases of an event ("perishable" data), can be particularly methodologically challenging.

2. NOAA needs greater capacity to collect, curate, store and share such data, in keeping with open science and human ethics standards.

3. Both conventional (e.g., surveys, interviews, participant observations, experiments) and less conventional (e.g., social media, citizen science and crowdsourced databases, smartphones, mobile apps) data sources offer rich human observational data about access, interpretations, or responses to weather information, attitudes and reactions to weather risk, and engagement in or barriers to protective action. Effective use of these heterogeneous data requires effective methods for data integration.

4. Also needed is research on new methods to effectively acquire and decipher these data in order to provide continuous, relevant feedback for product and service delivery.

Critical Actions for ID-6:

ID-6.1. Metrics development efforts: a) require research to define the suite of relevant and meaningful outcome variables (i.e., dependent variables, predictands) to measure, particularly for mission-critical themes (e.g., effective IDSS, effective risk communication, etc.), b) should not be static but need to evolve to incorporate new measures over time, c) must take care not to generalize findings beyond what is valid (e.g., populations, hazards, scenarios, measures, etc.).

ID-6.2. Particular effort should be given to support real-time collection of data for specific weather hazards when they are threatening. While such data are notoriously difficult to collect, they are highly useful, and it is important for resources to be provided to develop a plan for gathering these observational data. Such knowledge is essential for understanding how people are accessing and interpreting forecast information, assessing their risk and evaluating options, and making protective decisions.

ID-6.3. Consistent with open and transparent science initiatives outlined above, encourage publication of social and behavioral science data collection instruments (e.g., surveys, experimental design, interview protocols) and, as allowable per policies protecting human subjects, datasets.

Information Delivery Recommendation Outcomes:

These investments in a) achieving highly reliable, fully accessible weather information delivery to support inclusive and open science (ID-1 to ID-3) and b) social, behavioral and interdisciplinary hazardous weather-event-specific and baseline observations, data assimilation and analysis (ID-4 to ID-6)—will advance weather sciences as well as NOAA's mission. They will: enhance weather information services, increase innovation, and improve diversity at NOAA as well as within the environmental science community in general; provide more equitable access to all communities, including traditionally underserved communities, enhance social and environmental justice; and support a geographically distributed workforce, broadening access to talent, and supporting an agile and effective workforce that can be mobilized during times of crisis. They will also address NOAA's mission critical mile, by creating and improving:

- Systematic, holistic data and knowledge about users' informational needs given their (heterogeneous) risk management and decision-making contexts.
- Research on perceptions and uses of forecast uncertainty and confidence, their effects on risk assessment and decision-making, and critical moderating variables (e.g., barriers to taking action), emphasizing the concerns of underserved communities.
- Improved metrics and expanded approaches for measuring and tracking changes in the utility and effectiveness of weather information delivery efforts.
- Quantification of uncertainty and confidence across the spectrum of weather and water phenomena through expanded use of high-resolution models, ensembles, and AI (trustworthy, unbiased), driven by constituent needs.
- New methods will support adaptive information synthesis and communication to address information needs for users, decision domains, hazards (single or multiple), and hazard life courses; increased customization will characterize impacts from various hazards and develop metrics to prioritize these impacts and provide effective real-time IDSS.
- Reproducible, generalizable, and causal research with rigorous research designs (e.g., experimental and quasi-experimental designs, longitudinal studies and analyses, path modeling, and qualitative methods) will enhance weather information for IDSS.

7. Foundational Element Priorities for Federal Investment

There are four cross-cutting foundational elements - science, computing, workforce development, and the Weather Enterprise - that provide the essential underpinning for the three pillars just discussed. All four foundational elements are critical and are required to achieve NOAA's vision of a Weather-Ready Nation (WRN).

7.1 Science - Behavioral and Social Science, Earth System Science, Emerging Sciences, and Education and Research

Science is inseparable from the vision represented in this report of how investments over the coming decade will return incredible value to the citizens and commerce across the United States. Much of this science has been presented in the pillar sections; yet there are several areas of science that are addressed separately. Two areas of science that are core contents in both the pillars and foundational element sections are behavioral and social sciences, and Earth system science. These, in combination, are at the core of where the greatest gains can be made over the next decade and warrant this additional focus. Also, this section highlights emerging interdisciplinary sciences and weather applications (with a focus on AI and ML) as a critical area that has rapidly growing impacts within the forecasting domain. Another area evident throughout the pillars is the increasing need to support early readiness level (RL) science that NOAA requires but other agencies are less likely to support.

7.1.1 Behavioral and Social Sciences

The importance of advancing the social and behavioral sciences across the Weather Enterprise cannot be overstated in order to optimize weather information services so that they are value-focused and deliver optimally on NOAA's mission of saving lives, protecting property, and bettering the U.S. economy. Over the past twenty years, NOAA and the NWS have made tremendous progress in prioritizing behavioral and social sciences as they strive to deliver on their vision of a WRN. Yet, much more is needed.[20] Advancing social and behavioral sciences in the Weather Enterprise is critical as we look to a requirements and value-based prioritization process to drive the entire pipeline.

The overall infrastructure, customization, and understanding of the "mission critical mile" have lagged behind as opportunities and needs have grown. Robust and objective data of all kinds are critical to NOAA's future success, yet social and behavioral sciences data have garnered relatively less systematic attention. Such data can be particularly challenging to collect, given a) their perishable nature during rapidly evolving and fast-paced events; b) the importance (and current lack within NOAA) of scientific infrastructure and analytic capacity to support systematic, routine collection and use of baseline data on weather information needs, uses, and outcomes; and c) the scientific challenges of collecting and analyzing unbiased social and behavioral data to meet community and key partner needs as well as social and environmental justice aims.

NOAA has a strategic priority to assimilate social and behavioral data from users, assess and anticipate key user needs, and create and deliver responsive data and guidance products, including user-driven information as well as user-informed forecasts and warnings, in a virtuous cycle. Ultimately this requires a NOAA-wide vision and roadmap of open science and collaborative innovation in a relational model of weather information delivery, to democratize the Weather Enterprise, and to promote continuous weather information delivery feedback and improvement.

FE-1 Recommendation: Develop a weather-knowledge ecosystem, with social mechanisms to effectively leverage academic, governmental, and industrial partners to create, educate, apply, and advance weather information synthesis and modeling, and to integrate automated and human forecasting skills and weather communications and decision support. [Additional, more detailed, related recommendations can be found in the Information Delivery Pillar, Section 6.3.]

Critical Actions:

FE-1.1. Build capacity to develop multi-dimensional metrics, data repositories, and new data collection methods and standards for "baseline" (i.e., not event-specific) and event-specific "perishable" social and behavioral data, particularly for perishable data in the predictive phase of a threat—which poses methodological challenges—as well as in the aftermath.

7.1.2 Earth System Science

Although weather is an atmospheric phenomena, its state and evolution is dependent on interactions with adjacent Earth system components including the oceans, land, cryosphere and biosphere. Collectively these interdependent systems make up the Earth system and a holistic understanding of these systems and their interdependencies is critical for continued advancements in our ability to forecast weather and climate on all time scales. Advancing the science of the Earth system requires better observations of these connected systems, improved understanding of the physics and chemistry of each system and their interactions, and the development of Earth system models (see Box 2 in Section 5.2) with robust data assimilation to help understand and forecast the complex, complete system. As a result, most weather research and operational modeling is moving towards using ESMs as the foundational tool to advance the science and forecasts. NOAA has taken a major step in this direction recently with the adoption of the Unified Forecast System (UFS). However, there are many scientific elements of the Earth system that must be developed and improved upon to enable the UFS to become a state-of-the-science ESM. Given the vital nature of such science to NOAA's ability to make predictions, it is important that NOAA invest in basic (low RL) research that is specifically targeted to NOAA's needs (leveraging other agency science can help, but over reliance on that is not adequate).

FE-2 Recommendation: Continue to invest in understanding the basic physics, chemistry, and dynamics of the Earth system, and new data assimilation science, particularly in two-way coupled assimilation techniques that allow the new (and in some cases existing) Earth system observations to be incorporated into the UFS. (Additional, more detailed, related recommendations can be found in the Observation and Data Assimilation and Forecasting Pillars, Sections 6.1 and 6.2.)

Critical Actions:

FE-2.1. Increase direct support of critical research topics, in partnership with other federal and international agencies engaged in these topics, and catalyze the existing robust community of Earth system scientists to adopt and advance NOAA technologies (e.g., UFS and JEDI) as the preferred research and development platforms through EPIC and similar community initiatives.

7.1.3 Emerging Interdisciplinary Sciences and Weather Applications: Artificial Intelligence

The NOAA Artificial Intelligence Strategy[58] goal is to reduce data processing costs and provide higher quality and more timely scientific products and services for societal benefits. AI and ML methods have broad utility to improve effective utilization of observations, to improve accuracy and decrease latency in forecasting, and to produce targeted information products and support environmental justice. AI and

ML is fundamentally a data-driven process well-suited to the Weather Enterprise, but research along several axes is needed to make it effective.

First, AI and ML methods rely on data; accurate, high-quality historical training datasets are key for quality AI-based applications. Platforms for open science are needed to ensure a consistent set of data standards and AI-ready datasets to support online curated sharing of data and code that is broadly accessible to all communities, supporting diversity and environmental justice and allowing all researchers to participate in solutions. Second, scientific efforts must be developed around physics-based AI methods, hybrid NWP and AI schemes, and explainable AI techniques that use physics to explain what AI has learned and that support scientific discovery. AI technology must be robust, with explicit uncertainty quantification. Lastly, for AI methods to support effective human decision making, social science is needed for the establishment of trustworthy systems.

FE-3 Recommendation: Accelerate the NOAA AI strategy and expand efforts in data aggregation, scientific research and social science for AI.

Critical Actions:

FE-3.1. Establish accurate, high-quality, historical AI-ready datasets including observational data, analysis, and model output and make them available through open science platforms that allow all researchers and communities to collaborate, supporting diversity and environmental justice.

FE-3.2. Develop multi-agency cooperation around data sharing on open science platforms with common, open, cloud-optimized data standards.

FE-3.3. Develop research in physics-based AI, hybrid NWP, explainable AI, and robust AI, and uncertainty quantification.

FE-3.4. Create interdisciplinary teams of AI researchers, social scientists, and meteorologists, climate scientists, ocean scientists and more, focusing on risk communication and the creation of trustworthy systems.

7.1.4 Maximizing Investments in U.S. Science: A NOAA Weather Grants Program

The increasing complexity of NOAA’s mission and the evolving expertise required to meet this mission requires that NOAA take full advantage of the entire Weather Enterprise to determine the best paths forward in the future, advance science, supply the highly trained scientists needed for NOAA’s workforce, and assist NOAA in professional development and training for current employees.

Findings:

The involvement of tenure-track university faculty members in NOAA research is limited. NOAA funds the majority of its research via federal laboratories within the Office of Oceanic and Atmospheric Research (OAR) and associated Cooperative Institutes (CI) which are affiliated with a small number of universities. The CIs primarily hire university research staff to contribute to NOAA research working alongside federal employees. This situation also limits the involvement of graduate students in NOAA research.

The NOAA Weather Program Office (WPO) supports a very small competitive weather grants program (~$8 million per year) with several annual requests for proposals to university investigators. Successful grant proposals have a two year lifetime and the majority of these are associated with RLs suggestive of research that is very close to being transitioned to operational use. It is difficult for university faculty to support graduate students with two year grant lifetimes. Ideally investments would extend into very low RLs to focus on more fundamental questions of interest to NOAA, such as future observation systems, data assimilation methods, and numerical weather prediction model development. NOAA has identified data assimilation expertise as a significant need for the NOAA workforce.

There is no clear path for a university faculty member with a great research idea that is central to NOAA research and operations to submit a proposal to the WPO for consideration and be evaluated for potential funding. Instead, NOAA defines the opportunities available for funding, which precludes consideration and funding of other potentially beneficial research topics. There is a critical need for a process by which research ideas central to the NOAA mission can be evaluated, funded, and, if successful, influence NOAA research directions and operations.

The university community is better placed to engage in high-risk, high-reward research that could rapidly advance the NOAA mission than NOAA researchers who are focused upon research closer to operational use. NOAA is not currently taking full advantage of our nation's great universities to advance the NOAA mission.

Increasingly massive HPC resources are a prerequisite to competitive accuracy in weather and Earth system modeling. More HPC power can translate into faster innovation, and the development of higher resolution models with more detailed representation of physical processes. However, hardware and software are inherently interdependent, and improvement can only be realized if the software can take advantage of new computing capacity. HPC resources must be provided to university researchers as part of their grant support. (see Section 7.2)

FE-4 Recommendation: Increase university involvement in NOAA research to gain assistance in advancing the NOAA mission and in training the next generation of NOAA scientists. This should include, as appropriate, leveraging partnerships with other funding agencies, e.g. NSF.

Critical Actions:

FE-4.1. Investment options to consider include:

- significant increase in external grants funded through the WPO with an open-ended grants submission process;
- pattern the review processes after those used by NSF; fund research over a broader range of readiness levels; employ a temporary program director as done by NSF ("rotators") to enhance professional networks at NOAA; emphasize diversity, equity, and inclusion in proposal requirements;
- grant durations of three to five years to support graduate students with a focus on those working on a PhD; early career grants to young tenure-track university faculty members; emphasize special areas of need as determined by NOAA.

FE-4.2. High performance computing resources must be provided to engaged researchers as needed to make sure grant projects can be successful.

FE-5 Recommendation: Create multi-university research consortiums to address critical research issues for NOAA. These could be patterned on the highly successful NSF Science and Technology Center programs.

Critical Actions:

FE-5.1. The first NOAA consortium should be focused upon data assimilation as a critical need for NOAA. There is no federal agency that directly funds basic research in data assimilation, yet the need is great and experts in this area are defined as a critical NOAA workforce need.

FE-5.2. Support a robust, thriving, interdisciplinary and convergent weather information development and delivery research program in partnership with other public and private research organizations.

FE-5.3. Advance open science efforts to deliver user-oriented weather forecast information for dynamic, interacting weather hazards, and social and technological systems.

Science Recommendations Outcomes

More university tenure-track faculty members engaged in NOAA research through mutually beneficial collaborations that directly contribute to the NOAA mission. More graduate students, including PhD students, trained and ready to be hired by NOAA in critical mission areas. More investment in high-risk, high-reward research to rapidly address new challenges. Multi-university consortiums addressing the most pressing NOAA Research problems and advancing the NOAA mission. New training programs to help current NOAA employees develop new skills needed to address the complex problems of tomorrow using the best approaches. Achieve state-of-the-science high-resolution forecasting capabilities and accelerate numerical model development and liberate research-to-operations bottlenecks by improving the turnaround of research experiments.

7.2 Computing

Improvements in weather forecasts are directly limited by the availability of sufficient computing resources to develop, test and operate next-generation forecasting technologies. In this section, we identify current limitations and 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 7: 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.

Findings:

1. Weather forecasts have improved dramatically in the past fifty years in large part due to investments in the science of, observations supporting, and computing necessary for numerical weather prediction (NWP). Numerous factors related to these continue to drive the need for greater HPC capacity, including higher resolution of models and massive increases in data, ensemble forecasting, convective weather requirements, sub-seasonal, seasonal and interannual forecasts, the need for reforecasts and reanalyses, and the 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.

2. A comprehensive plan for the HPC needed to support both the research and operational weather needs of NOAA and its community partners over the next ten years is not available. 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.)

3. 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 few exaflops of operational computing by 2031. Exascale computing systems are already being installed at Oak Ridge National Laboratory (1.5 exa floating point operations per second (EF)) and Argonne Labs (1.0 EF) and it is likely that these national HPC laboratories will approach 100 EF by 2031. Because HPC resources are essential to achieving the outcomes discussed in this report, it is reasonable for NOAA to aspire to a few percent of the computing capacity of these other national labs at a minimum. Substantial investments are also needed in weather research computing. To achieve a 3:1 ratio of research to operational HPC, NOAA will need an additional 5 to 10 EF of weather research and development computing by 2031. Since research computing generally does not require high-availability HPC, it should cost substantially less than operational HPC and should be able to leverage a hybrid of outsourced, cloud and excess compute resources.

4. 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.

5. 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.

6. 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.

7. 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.

8. While advances in numerical weather prediction have been the primary driver for increases in computing requirements to support weather forecasting, a rapid increase in new observation systems, advances in data assimilation complexity, and new applications in artificial intelligence are also rapidly increasing the need for computing resources to support weather applications that permeate all aspects of NOAA's and the NWS's weather mission.

FE-6 Recommendation: The federal government should immediately invest in substantially more computing resources dedicated to weather forecasting research, development, testing and operations, and demonstrate a long-term intent to sustain the United States as the leader in computing technology and resources for weather. Based on the preliminary estimate above for future NOAA HPC requirements, we recommend a goal of at least a 100X increase by 2031.

Critical Actions:

FE-6.1. 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 UFS.

FE-6.2. The open science and community engagement recommendations elsewhere in this report require weather enterprise access to lower security HPC assets that are not constrained by the expense and security requirements of operational assets.

FE-6.3. Owing to transport limitations, an increasingly larger portion of value-added data processing should be done within the HPC computing facilities by both NOAA and weather community users in order to allow the nation to take full advantage of NOAA data.

FE-6.4. The investments should be balanced across all aspects of computing, including data storage, access and transport.

FE-6.5. Immediately undertake a study to determine the full computing needs of the weather research and operations community, including that of its research partners, and report to Congress the results.

FE-7 Recommendation: NOAA must immediately invest in long-term programs to convert, prepare for, and leverage new and emerging high performance computing architectures such as cloud, GPUs, exascale and quantum.

Critical Actions:

FE-7.1. Refactor the UFS to leverage emerging technologies.

FE-7.2. Invest in a paradigm and 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.

7.3 Workforce Development

Meeting the strategic goals of a WRN requires new employee skill sets and a more diverse workforce. NOAA should catalyze a substantial increase in the pipeline of next-generation researchers, technicians, and practitioners skilled to work in the necessary complex modeling, observation, assimilation, communication and computing environments by enhancing and catalyzing institutions, programs and other initiatives that can teach these disciplines, and make dedicated modeling, data, and computing platforms available to support such programs. Investments in education and training, both initially and ongoing, is essential to maintain a competent, diversified workforce, particularly given the rapid pace of change in today's technology.

Findings:

1. NOAA needs better strategies for creating and regularly updating competency models and knowledge repositories, as well as sustained partnerships with academia, to develop new and evolving academic programs and training approaches, hiring pipelines, and robust, reliable and agile open science infrastructure and organizations.

2. The hiring of employees with the advanced skills needed by NOAA is hindered by pay disparities between the public and private sectors and ossified federal job classifications. This workforce situation is a dramatic shift from the past when NOAA positions were the most highly desired and the skills needed were well defined. The NOAA workforce requires a new framework that includes a broader range of degrees and skillsets, and focuses upon lifelong learning that maximizes the contributions of the United States science enterprise.

3. Diverse groups of people are better at problem solving than non-diverse groups, while effective outreach to the thousands of communities across our nation on weather preparedness and safety requires a diverse workforce to recognize and understand cultural differences in how weather information is consumed. NOAA has a growing need for a diverse workforce.

4. NOAA cannot develop its future workforce without fully engaging the talent and expertise within the nation's universities. Universities already are working with K-12 schools to increase science

literacy and instill a lifelong love of learning. Faculty are at the cutting edge of science advances, such as data assimilation, AI and ML, and quantum computing; many faculty members engage in high-risk, high-reward research that is difficult for government service agencies to pursue owing to their missions and required budget oversight. University faculty are a huge, untapped resource that could be used to help NOAA solve problems, diversify its workforce, and regain its international leadership in weather prediction.

5. NOAA has identified a serious gap in workforce expertise in data assimilation. Data assimilation plays a critical role in addressing nearly all NOAA mission areas. Sustained workforce development in data assimilation is critical for the United States to gain global leadership in weather prediction and for NOAA to provide the best services to the public.

6. Evidence suggests that university undergraduate and graduate students supported by NOAA and conducting research important to NOAA are more likely to view NOAA as a viable and exciting career option.

7. Many of the challenging science issues that NOAA must address are complex and cannot be mastered fully within the time scales of university graduate education, emphasizing the need for continual employee training and development. Access to tutorials and use cases helps researchers gain insight into the use of native cloud tools and their value to derive insight from data hosted in the cloud. Different communities of practice are compiling expertise and lessons learned from cloud-based work using NOAA datasets, while others are developing tools and tutorials to facilitate big data analysis in the cloud. Online tutorials can assist in providing new skill sets for NOAA employees and encourage lifelong learning.

8. Where NOAA has invested in open science (e.g., unified forecast system, national water model), NOAA managers report that this has facilitated and contributed to more effective recruitment, retention, and positive professional experiences for NOAA scientists and practitioners.

FE-8 Recommendation: Develop a pipeline of diverse talent from K-12 students to undergraduate and graduate students to NOAA employees to lifelong learning and professional development.

Critical Actions:

FE-8.1. NOAA and other federal agencies (NSF, U.S. Department of Education, etc.) should invest in programs to develop a pipeline of next- generation researchers, engineers, and practitioners that are skilled in and can operate or develop weather technologies that exploit and advance emerging computing architectures, data assimilation programs and observing systems. This includes catalyzing academic partners to develop programs for all levels of students (undergraduate through post-doctorate) as well as programs to educate the existing workforce in NOAA, academic and private sector institutions.

FE-8.2. Be opportunistic to entrain the best international talent into NOAA.

FE-9 Recommendation: Develop an enterprise vision for workforce education and training at multiple degree levels that is flexible enough to accommodate different line office needs and leverage existing resources available to the community.

Critical Actions:

FE-9.1. NOAA should establish employee professional training programs in needed areas of expertise (e.g., cloud and emerging new HPC computing technologies, open source code development, AI and ML, data assimilation, instrumentation) to increase retention and remain agile amidst technological change.

FE-9.2. Eliminate gaps in expertise through partnering, enabling NOAA resources to be focused on innovation and applications rather than replication.

Workforce Development Recommendations Outcomes

- A talented, diverse, and engaged NOAA workforce that can adapt quickly to new situations in which NOAA continually hires the best university graduates at multiple levels and provides employees with lifelong training and professional growth
- Re-establish NOAA's global leadership in data assimilation, observations, modeling and prediction of the Earth system through recruitment and training of the best workforce and assisted by NOAA becoming a new world leader in open science collaborations.

7.4 Weather Enterprise

The U.S. Weather Enterprise comprises three multi-disciplinary sectors - government, private sector, and academia - that contribute to all aspects of the science of weather, weather forecasting, product development and delivery, to improve the economy. Each sector plays a critical role in understanding, observing, forecasting, and providing decision support to inform people and their communities of critical weather information in the national interest (see ID-3). The Weather Enterprise provides societal benefits for applications from agriculture to water management. A key National Research Council Second to None Report[16] recommendation is to "Leverage the Entire Enterprise" to meet expanding and evolving user needs. This PWR Report recommendation emphasizes the value of Weather Enterprise integration consistent with the Second to None Report "*so that all domestic users of weather information can receive data in the most efficient and effective manner possible.*"

The government, private sector, and academia each contribute to the overall enterprise and constituent elements of environmental monitoring, modeling, and decision support (Figure 15). National and global needs require consistent, stable, reliable, and secure data sharing through effective enterprise integration across all weather-related sectors. Each of the elements in the figure, monitoring, modeling, and decision support, need to evolve and be increasingly interconnected to realize the objectives of Weather Enterprise integration. The NOAA SAB EISWG Data Dissemination report[36] Recommendations 3 and 4 outline a plan to address NOAA operational data dissemination challenges by leveraging content delivery networks and accelerating migration to commercial cloud networks for secure, reliable connectivity across the enterprise.

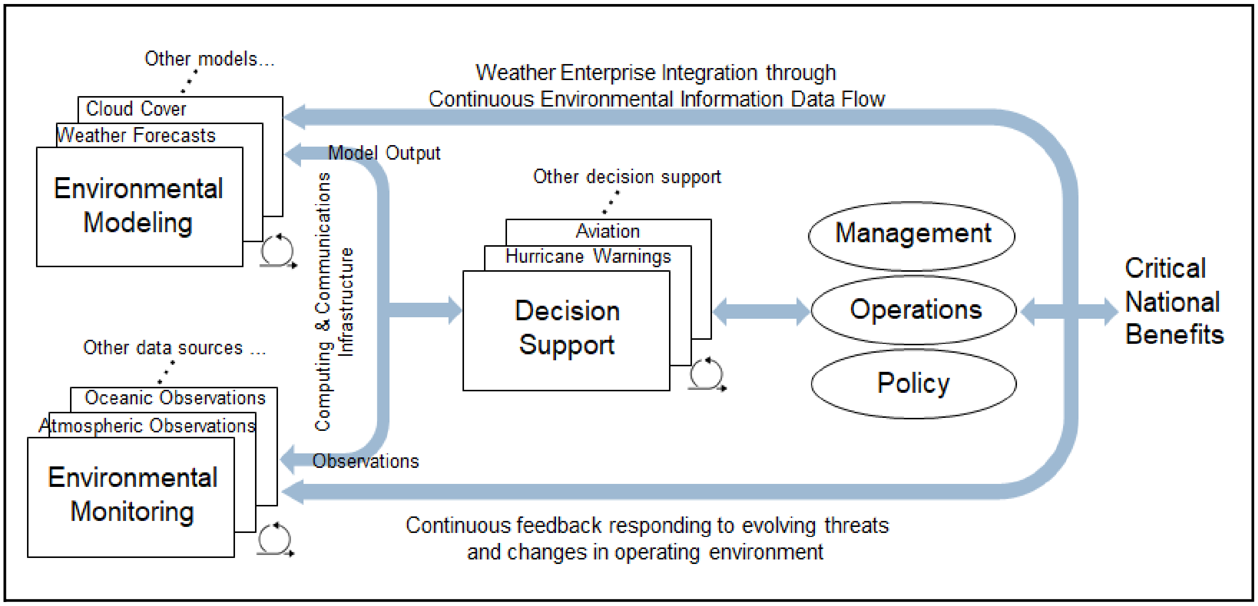


Figure 15: Weather Enterprise Integration Data and Information Flow for all Sectors

The Weather Research and Forecasting Innovation Act of 2017 (WRFIA) instructs NOAA to prioritize improving weather data, modeling, computing, forecasting and warnings for the protection of life and property and for the enhancement of the national economy. The NIDIS Act of 2018 instructs NOAA to establish the Earth Prediction Innovation Center (EPIC) to accelerate community-developed scientific and technological enhancements for NWP. NOAA administers the Unified Forecast System (UFS) as a community-based, coupled, comprehensive Earth modeling system. The UFS numerical applications span local to global domains and predictive time scales from sub-hourly analyses to seasonal predictions. UFS is designed to support the Weather Enterprise and to be the source system for NOAA's operational numerical weather prediction applications. Further, the Interagency Council for Advancing Meteorological Services (ICAMS) fosters collaboration to ensure societal benefits with information spanning local weather to global climate.[59] WRFIA, NIDIS, EPIC, UFS, and ICAMS success depends on reliable, stable, and secure data enabled by Weather Enterprise integration for information flow across all sectors.

Community engagement in UFS via EPIC is needed with commensurate funding and support to address gaps. Stable long-term government funding is required for researchers across NOAA, Cooperative Institutes, universities, private sector and federally funded research and development centers (e.g., National Center for Atmospheric Research (NCAR)), to work in concert with the EPIC program to advance U.S. capabilities in UFS to serve the public good. Resources are needed for Weather Enterprise integration to ensure reliable data availability for sustainable collaboration across federal agencies, academia, and the private sector among HPC, cloud computing, data assimilation, production, and management for U.S. leadership in weather forecasting. Global collaboration across the Weather Enterprise can be accomplished through NOAA leadership in a global reanalysis consortium with the World Meteorological Organization (WMO) and the Intergovernmental Oceanographic Commission (IOC). NOAA leadership in Weather Enterprise integration data flow can ensure essential data are available for modeling and decision support through collaboration with the private sector, academia, and WMO/IOC. NOAA Weather Enterprise integration should align with WMO initiatives to strengthen exchange of observational data across the globe to improve weather and climate services: WMO Unified Data Policy, Global Basic Observing Network, and Systematic Observations Financing Facility.[60]

A Weather Enterprise integration approach can expand availability of observations from multiple sources, including data buys, small satellites, radars, surface networks etc. to increase overall data availability and access. With significant progress in observations, models, and decision support available from the private sector and academia, NOAA can benefit from clear, well-defined processes to select, acquire, assimilate, and assure ingress and egress of authoritative source of truth for data for Weather Enterprise integration.

Partnerships across NOAA, other federal agencies, universities, private companies, and international operational centers can be leveraged for coupled, reliable, and secure data assimilation. NOAA's Joint Effort for Data Assimilation Integration (JEDI) is a framework for streamlining such collaboration. NOAA can realize benefits from maintaining cognizance of ESM development by other agencies and national organizations (i.e., NSF/NCAR, DOE, NASA) leveraging developments through partnerships. NOAA collaboration with NASA, USGS, EPA, USACE, USDA, through sustained investments in water and air quality data assimilation can improve forecast product skill and decision support in the national interest.

FE-10 Recommendation: Create a NOAA-wide function to provide Weather Enterprise data integration and dissemination strategy and sustained operational oversight to ensure preparedness and response.

Critical Actions:

FE-10.1. Invest to ensure availability and continuity of data and information across NOAA, including ingest and egress from, and to, all appropriate participants across the Weather Enterprise, to improve weather data, modeling, computing, forecasting and decision support, including severe weather warnings.

FE-10.2. Invest to implement EISWG Data Dissemination report[36] Recommendations 3 and 4 to leverage content delivery networks and accelerate migration to commercial cloud networks for all integration and dissemination of NOAA weather-related information across the Weather Enterprise for societal benefits.

8. Immediate First Steps

The need to invest in the development and delivery of weather information is urgent if we are to keep pace with potential advancements and ultimately improve our ability to protect lives and property, to broaden the communities served with relevant weather information, and to promote economic vitality in a time of rapidly changing weather trends and extremes.

Each of the recommendations in this report has been called out as high priority by the combined voice of the PWR Report Team's many subject matter experts; yet there is an important acknowledgement that not all of these recommendations can be started at once. As such, this section of the report calls out several areas and efforts that the team deems critical for early prioritization and action. For some efforts, the existing gap (and resulting setbacks) between what is currently available and what is needed is so large, or critical, that action must be taken immediately to mitigate against further setbacks. For others, the resulting benefits from a rapid implementation of emerging technologies are so significant that they justify early attention. Additionally, some recommendations are dependent upon others being completed prior to being started. As such, the PWR Study Team has highlighted the following immediate first steps, across four core areas, reflecting an extreme immediate need, or the long lead time required to spin up a critical component:

RESEARCH & DEVELOPMENT:

1) Accelerate development of an **Earth system modeling (ESM)** framework approach to improve forecast accuracy and lead time (Forecasting, Priority Area 1). This framework would be transformational and highly beneficial across many fronts. The framework is needed to bring all of the parts of this report together efficiently and effectively, as essentially every priority area within this report will benefit from its successful development.

2) Increase investments in **social and human behavioral data collection and sciences** to better understand how weather products are used and to support co-development of improved products (Information Delivery, Priority Area 2; Foundational Elements, Section 7.1). Immediate investments are needed to address service gaps and systematically engage historically underserved and socially vulnerable populations. Expanded capacity is needed to coordinate and support weather information delivery in a holistic approach that cuts across hazards and the full diversity of decision makers and weather information users. New metrics, inclusive design principles, and systematic research and evaluation strategies will also enhance the development and delivery of user-oriented, timely, meaningful, skillful (accurate), usable, and actionable weather information.

3) 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 (Observations and Data Assimilation, Priority Area 2). Early support of innovative data assimilation research and development, especially at early RLs, will prove to be the catalyst for many related and downstream benefits. The effective utilization of existing and future observations all depend on the rapid and significant advancement of data assimilation capabilities.

INFRASTRUCTURE:

4) Fully implement and rapidly expand the existing plans for improved **weather data dissemination**, increasing understanding through open science approaches, and expanding applications through weather industry partnerships (Information Delivery, Priority Area 1). Today's operational data dissemination challenges are real and significant. While the existing plan[61] is commendable, its solutions are still insufficient and slow. The United States stands alone in its highly successful Weather Enterprise partnership, which depends upon a reliable infrastructure with unfettered access to core data assets. Restrictions and outages in this area cut into the very fiber of this success and must be mitigated with utmost urgency.

5) Expand **high performance computing (HPC)** capacity by two orders of magnitude (over ten years) to support operational forecasts and data dissemination and provide critically lacking capacity in U.S. weather research (Foundational Elements, Section 7.2). HPC must be an immediate and ongoing investment. HPC shortfalls and requirements have been highlighted in many of the report's recommendations where it is called out as critical for success, not only for operations, but especially so for research. Without sufficient HPC investments, the loss of potential advancements is tremendous and cannot be overstated.

6) Fill gaps in existing **Earth system observing networks** with existing, proven or augmenting technologies to expand coverage, especially in underserved regions; existing observing system technologies, including private sector, academic, and unattended observing systems, must be immediately prioritized for deployment to fill current gaps (Observations and Data Assimilation, Priority Area 3). There is a backlog of well-known observational gaps with established potential to fill them. These sensors exist and can be deployed; it is a matter of capacity alone. Such investments quickly support improved weather forecasts from minutes to two-year lead times, enable scientific advances, and engage academia and the private sector.

ACTIONS & IMPACTS:

7) Support **reanalysis and reforecasting** vital to Earth system model evaluation and improvement, to characterize extremes, and provide training datasets for artificial intelligence (AI) product applications (Observations and Data Assimilation, OD-5; Forecasting, FO-3). A plan to complete the reanalysis/reforecasts (RA/RF) for NOAA's forecast systems is absent and critical. A successful ESM effort is not possible unless a full plan for RA/RF with immediate execution is defined and completed. One of the known inhibitors of completing this plan is the absence of a dedicated HPC allotment for the task (see (d) above; Foundational Elements, Section 7.2). The success of completing this recommendation is critically important to all other modeling system efforts as well.

8) Target the **understanding and prediction of high-impact weather (HIW)** to match the urgent need imposed by climate trends, population and infrastructure increases, and disproportionate impacts on vulnerable communities; including exploring new innovations with AI and ML applications (Forecasting, FO-6). A few examples of HIW are fire weather (and associated air quality), water extremes (floods and drought), heat, hurricanes, and severe thunderstorms. 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.

9) Target **water cycle extremes and their cascading impacts** to improve flood and drought prediction and to enable forecast-informed reservoir operations (Observations and Data Assimilation, OD-8; Forecasting, FO-4). Water cycle extremes, i.e., drought and flood are leading causes of economic and human disruption, and 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:

10) Develop **improved, increasingly objective, methods to balance investments** across the weather information value chain and expand efforts to more precisely target future investments. It is critical that NOAA immediately develop more systematic methods to prioritize investments, including improved metrics to measure success, set goals, and focus resources. Ideally this effort will integrate the recommendations from this report with its current priorities. It is also recommended that NOAA develop and or revise its own implementation plans with timelines that respond to the recommendations. In addition, a gap

analysis may be needed to identify unfunded requirements to support near- and long-term funding decisions. Not only will these methods better inform NOAA leadership, they will also provide Congress additional tools to prioritize investments for the greatest impact. Ideally these methods will be structured, cross line offices, and promote an integrated approach to budget decisions.

The benefits of investing in these ten core first steps will be tangible and rapid. It is also critical that the implementation of each should: leverage open science approaches; consider investments in research and development partnerships across all sectors of the Weather Enterprise; and consider workforce development opportunities.

9. Report Summary and Suggestions for Future Engagement

The NOAA SAB was charged by Congress with providing policymakers the information necessary to prioritize federal investments in weather research and forecasting over the next ten years. The NOAA SAB's PWR Study Team leveraged a broad and experienced community of subject matter experts drawn from across sectors to develop and integrate the requested information in this report. The Study Team provided investment priority recommendations with short- to long-term goals spanning the coming decade (Sections 6 and 7). The Study Team also identified immediate first steps that filled especially critical gaps, or required long lead times to produce a downstream benefit required by other dependent recommendations or critical actions (Section 8). This report is the immediate outcome of this effort but ideally only a starting point to grow a stronger Weather Enterprise.

The recommendations provided here are based on a snapshot of where the Weather Enterprise is today, and the anticipated trends that will influence it into the future. The expected rapid evolution of external world influences over the next decade will result in changes that NOAA, and the Weather Enterprise, should continue to anticipate, and ultimately take advantage of, to best fulfil their missions. As a result, priority areas for investment may evolve, and new priority areas may arise. Critical actions may need to be adjusted based on advances in science, technology, capabilities, or public need. Long-term recommendations may need revisiting at regular intervals if they are to remain relevant for a decade in this rapidly changing environment.

Keeping pace with rapid change is not a new challenge for NOAA. As noted in Section 4 of the PWR Report, this challenge was similarly described a decade ago in the National Research Council Second to None report.[16] To help meet this challenge, the PWR Study Team encourages multiple levels of engagement between NOAA and the broader community, including: at the Weather Enterprise level through open science approaches, at the government leadership level through interagency coordination, and at the advisory level through continued engagement with the SAB and others.

Embracing an open science community approach (ID-1) will enable government, industry and academic researchers and practitioners to increasingly work together to promote innovation that advances Earth, social and human behavioral sciences, and their application to weather information needs. Open science and collaboration is an efficient pathway to successfully implement many of the PWR Report recommendations. Supporting new employment models for entraining an increasingly technical and diverse workforce (FE-9) engaged through the open science process will further contribute to the broader use of new innovative approaches.

The pathway to higher quality products and services will require coordination across federal agencies. The Interagency Council for Advancing Meteorological Services (ICAMS) mission is "ensuring U.S. global leadership in meteorological services ranging from local weather to global climate." This is enabled through an Earth system science approach that includes inspiring the next generation of interdisciplinary scientists.[34] Support for the Earth system science approach, and coupling to social and human behavioral sciences to develop the knowledge base on how products and services are most effectively used by a diverse public, are identified in the PWR Report as immediate first steps. ICAMS will provide the leadership-level forum to coordinate and leverage support for these increasingly interdisciplinary and cross agency weather science needs.

The NOAA SAB structure is available for Congress and the agency to engage in the future. In addition to the NOAA response to this report, keeping pace with external change and internal progress will require iterative reassessments on a regular basis. The NOAA SAB, joined by its network of working groups, leverages broad community experience that can be used to assess progress on the PWR Report recommendations, can update and refine these recommendations as needed, or can develop new recommendations prompted by changing circumstances. The PWR process has further demonstrated the SAB's capacity to leverage a vast community of experience via the temporary engagement of subject matter experts on specific topics. The layered group consensus approach used here could be repeated in the future, for example, at the midpoint of the decade. During that time, progress will be made, and increasingly objective methods may be available to prioritize the next level of investments required to meet the Weather Enterprise's evolving set of challenges.

The recommendations provided in this report build on the foundation for weather research and forecasting that exists in NOAA, and across the Weather Enterprise. Taken together, the recommendations are transformational. Investment will transform how weather information is developed and delivered across the nation. If updated through iterative collaborative processes as described here, the recommendations provide an adaptable framework for sustained improvements. The lasting impact of investments will be a more vibrant weather-informed economy; a nation that is more prepared, is better able to respond, and is more resilient to extreme weather; and a nation that provides environmental justice and equity for all.

Appendices

I. Study Approach and Meeting Log
II. Participants
III. External World Summary Table
IV. Summary Recommendations Table
V. References
VI. Acronyms
VII. Glossary

Appendix I. Study Approach and Meeting Log

The year-long Priorities for Weather Research (PWR) Study included three phases: a) a high-level scoping phase, b) a broadly collaborative information gathering phase, and c) an iterative and deliberative report integration phase.

Scoping Phase. The NOAA Science Advisory Board (SAB) first formed the PWR Scoping Team consisting of representatives from the SAB, the SAB's Environmental Information Services Working Group (EISWG), and the NOAA line offices. The Scoping Team developed a statement of purpose, further defined the study scope and boundaries to identify a far reaching but achievable goal, and devised a strategic framework, a PWR Study Team structure, and general criteria for an overarching investment strategy to accomplish the goal.

The Scoping Team's articulated purpose for the PWR Study was to evaluate and prioritize potential investments in a requirements-based framework to advance weather research and forecasting capabilities over the next decade. Boundaries were set to focus this broad scope on the most important aspects of the information requested by Congress. Key boundaries included a) the Study Team would adopt the WRFIA definition of weather (time scales from minutes up to two years); b) the focus would be on investments in NOAA, the core federal agency in the Weather Enterprise, with an awareness of what other federal agencies, the private sector, and academia, can provide to advance the research and forecasting priorities; c) the primary focus would be on future and planned investments; d) the Study Team would not develop independent requirements or cost estimates; and e) due to the breadth of the topic and limited time for completion, the study would focus on high-level aspects and would not perform detailed analyses into specific aspects of any study component. The Study Team structure, and the approach for the information gathering and report integration phases, are described below. The charge to the PWR Study Team produced by the PWR Scoping Team was approved by the SAB on 15 March 2021.

Study Team Structure (see Figure 16). Multiple teams were established to accomplish the study goal in the short time frame. The ***SAB Steering Team*** monitored progress, provided oversight, and, as required, provided a communication pathway with NOAA leadership. The ***Executive Study Team*** led the overall effort, ensured effective communication and coordination across Task Teams during the information gathering phase, and was the core writing team that led the final report integration effort. Three ***Task Teams*** pursued parallel efforts to gather and analyze information for each of the three pillars: Observations and Data Assimilation, Forecasting, and Information Delivery, producing draft pillar recommendations for consideration during the report integration phase. The ***Cross-Cut Team***, consisting of representatives drawn from each of the Task Teams and the Executive Study Team, assembled and consolidated recommendations from across the pillars within the cross-cutting foundational elements (science, computing, workforce development and the Weather Enterprise).

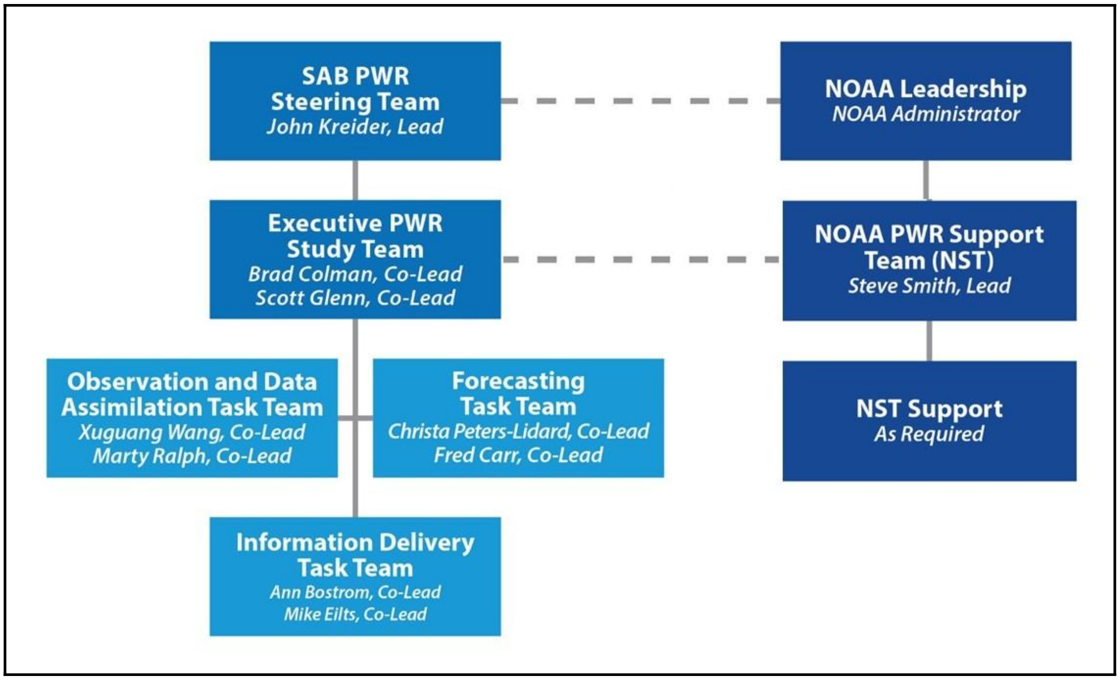


Figure 16: Diagram of the PWR Study Team Structure

Information Gathering Phase. Following approval of the SAB PWR charge document, the Executive Study Team, the three PWR Task Teams, and the NOAA Support Team (NST) were formed to work along parallel but coordinated tracks during the information gathering phase. The NST developed a document repository with over 100 relevant reports and publications. The documents were supplemented with fifteen information briefs for the PWR Study Team to provide a starting point on the current capabilities and future plans. The Executive Study Team collected and consolidated information on the external context (see Section 4) that could influence the development of PWR recommendations and how those recommendations may eventually be implemented. This provided the initial starting point and the external framework for the three Task Team efforts to gather information on each of the three pillars.

Central to the Task Teams' information gathering was the design and delivery of virtual mini-symposia. Each Task Team engaged a broad distribution of external subject matter experts (SME) who provided written input on potential mini-symposia topics. Drawing from the SMEs and the NOAA community, each Task Team organized short talks and discussion panels on a range of topics for each mini-symposia in late June and early July, 2021. Draft recommendations were then prepared for each pillar and presented for comment and feedback to the full PWR Study Team including the SAB Steering Team.

Starting early in the process, Task Teams were charged to reduce the overall topics of consideration and only retain those where value and impact were perceived as critical. Each Task Team documented its findings and observations based on its reviews of recommendations from the NOAA material provided by the NST and the many briefings from scientists and professionals received throughout the process. Each Task Team worked to draft a set of top recommendations through a collaborative process. Considerable effort and time were committed over several months to the discussion of the draft recommendations, and the background, findings, and observations that support the recommendations. Informed by these parallel efforts, the final full set of recommendations were compiled for the PWR Report (see Figure 17).

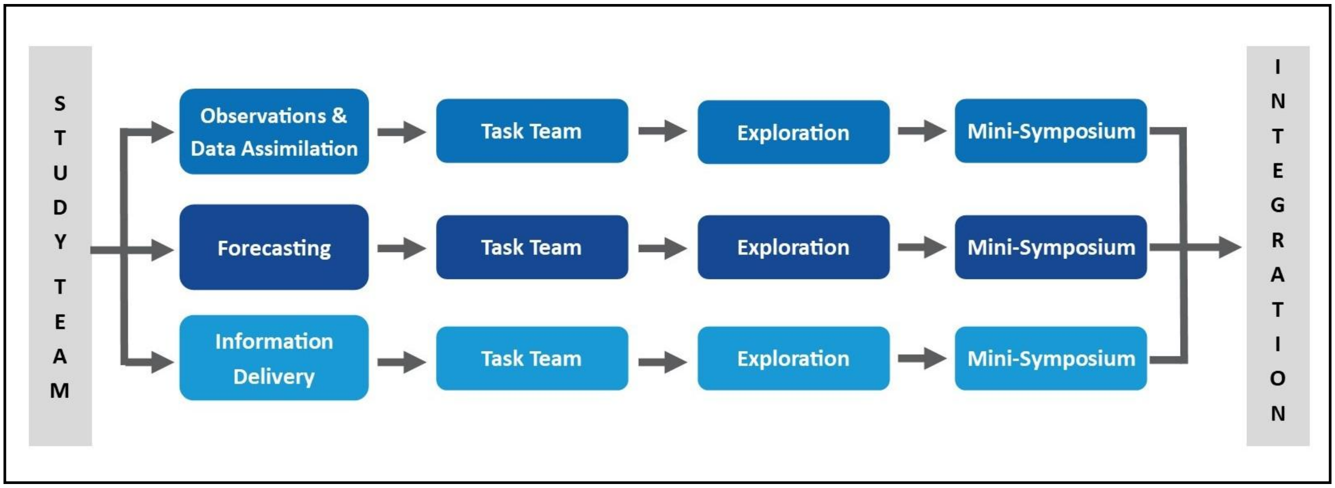


Figure 17: Parallel Tracks for Mini-Symposia

Integration Phase

Draft recommendations from each pillar were assembled by the Executive Study Team (which includes the co-leads from each Task Team), to align content across the pillars, identify common threads, address redundancies and further refine the recommendations. A Cross-Cut Team that included representatives of each of the Task Teams was formed to consolidate the common recommendations that aligned with the foundational elements. An extended outline for the full report was presented to the SAB at a public meeting in August of 2021. Working sessions with interested SAB members were scheduled for individual pillars and foundational elements in September and for a full draft report in November. Final priority areas for investment, recommendations and critical actions for each recommendation, are summarized in the table in Appendix IV.

Meeting Log

1. Scoping
    a. March 3, 2021 - Scoping meeting with NOAA AAs
    b. March 8, 2021 - Scoping meeting with NOAA AAs

2. PWR Study Team
   The Executive Study Team met weekly on Wednesdays from mid-March to mid-August 2021. During this time, the Task Team co-leads joined the meetings on the second Wednesday of each month. The last Wednesday of each month was a plenary session for the entire PWR team (Executive Study Team, full Task Teams, SAB Steering Team, and NST). Starting in mid-August, these meetings transitioned to include the full writing team, which was composed of the Executive Study Team, Task Team co-leads and Cross-Cut team. Between June and October 2021, the Task Team co-leads and the Cross-Cut team met with their respective teams as needed.

3. Task Teams
   The full Task Team for each pillar met primarily in June and July 2021 to draft their recommendations. Each Task Team held a symposium on the dates below.
    a. Information Delivery Task Team Symposium - June 29, 2021
    b. Forecasting Task Team Symposium - July 7, 2021
    c. Observations and Data Assimilation Task Team Symposium - July 8 and 9, 2021

4. NOAA Support Team
   The NOAA Support Team held 7 meetings in April and May 2021 to prepare materials requested by the PWR Study Team.

5. NOAA Briefings
   The PWR Team received the following briefings from NOAA to inform their efforts.
   a. May 4, 2021 - Discussion with Technology, Planning and Integration for Observation (TPIO)
   b. June 1, 2021 - NWS Strategic Plan
   c. June 3, 2021 - NOAA R&D Vision Areas
   d. July 1, 2021 - NWS Modeling Program
   e. July 12, 2021 - Data Assimilation
   f. July 13, 2021 - OAR Strategy
   g. July 15, 2021 - NESDIS
   h. July 29, 2021 - Aviation (for the Information Delivery Task Team)
   i. July 30, 2021 - Localized communication of geospatial weather information delivery (for the Information Delivery Task Team)
   j. August 4, 2021 - NWS Service Equity
   k. IDSS information delivery (for the Information Delivery Task Team)
   l. August 19, 2021 - Water briefing #1 (Precipitation Prediction)
   m. September 2, 2021 - OMAO
   n. September 14, 2021 - ICAMS
   o. September 30, 2021 - Water briefing #2 (“water on the ground”)
   p. October 19, 2021 - Water briefings #2 follow up discussion

6. Science Advisory Board meetings
   Science Advisory Board members who were not on the SAB Steering Team, Executive Study Team, or Task Teams were given multiple opportunities to provide input on this report throughout its creation. The SAB held public meetings on March 15 and 17, 2021; June 11, 2021; July 20 and 22, 2021; and August 25, 2021, where updates on the report were provided, followed by Q&A with SAB members. The SAB also held working sessions on September 28 and 29, 2021 and November 2 and 4, 2021 as additional opportunities for SAB members to ask questions.

Appendix II. Participants

Core Executive Study Team
Brad Colman *(report co-lead)*
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Bill Gail
Bill Hooke
Zhaoxia Pu
Marshall Shepherd
Bob Winokur

SAB Steering Team
John Kreider *(SAB Chair)*
Everette Joseph
Eugenia Kalnay

Observations and Data Assimilation Task Team
Marty Ralph *(co-lead)*
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Ron Birk
V. Chandrasekar (Chandra)
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Tyler Erickson
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David Gochis
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SAB Staff and Support
Cynthia Decker *(SAB DFO)*
Courtney Edwards *(project manager)*
Tiffany Atkinson
Bonnie Morehouse
Kathryn Olivieri

Appendix III. External World Summary Table

AREA #	AREA	RELEVANCE TO PWR PLAN	TRENDS, RISKS, AND OPPORTUNITIES OVER NEXT DECADE
1	NOAA end-users and their needs	NOAA mission is to serve its end-users	Expectation of ongoing accuracy, function, and service improvements
			Emerging use cases, such as automated transportation
			Growing need for integrated information, combining NOAA information with other data
			Growing importance of social science for effective user interaction; particularly as communication ecosystems evolve
2	Evolving societal vulnerabilities	Long term plans must be adaptable to changing conditions and needs	Changing climate
			Extreme events - temperature extremes, drought, floods, hurricanes, tornados, wildfires
			Water security (quality and quantity); food security
3	Justice, equity, diversity, and inclusion	Intention of legislation is to better serve all domestic users	Environmental justice and equity
			Gaps in data coverage
			Gaps in communication - risk, watches, warnings
			Promoting an even more inclusive Weather-Ready Nation
4	Public perception	Important for preserving and executing NOAA mission	Ongoing impacts of being buried in DOC
			Growing awareness and impact of WRN
			Growing but still controversial public support for climate science and action
5	Governance and budgets	Government is both funding source and major customer	Budgets increasingly volatile, dependent on party leading government
			Shifting federal-state roles and responsibilities
			Growing contribution of non-traditional funding (e.g., philanthropies) to NOAA mission topics
6	International	Many NOAA capabilities build on international collaboration	Growing capability and influence of other countries
			Increasing World Meteorological Organization interaction with commercial sector

			Growing global transportation, goods and services needs
7	Observation	Both situational awareness and forecast modeling/ and validation highly dependent on observations	Rapidly growing capability and viability of commercial satellite observations
			Emergence of mobile devices (phones, vehicles) as sources of spatially dense, lower-quality data
			Expanding observational needs of the Earth system approach
			Challenge of obtaining observation density to match current and future model resolution
8	Forecasting	Forecasts, warnings, outlooks, etc. are the primary products the public receives from NOAA	Expectation of ongoing accuracy, function, and service improvements
			Growing role of artificial intelligence and machine learning in analysis and forecasting;
			Importance of understanding how public receives, interprets and responds to forecast and warning information
			Forecast improvement strongly dependent on NOAA high performance computing capacity
9	Information dissemination	NOAA increasingly relies on commercial web and mobile dissemination tools	Rapidly growing demand for NOAA raw data
			Uncertain evolution of mobile devices and mobile apps, uncertain viability in emergency situations
			Growing challenges of information security
			Rapidly growing data volumes
			Expanding role of private industry in the “operational” delivery of forecast information
10	Enterprise	Partnerships provide leverage (capacity, resources, budget) for NOAA to perform its mission	Growing ability of enterprise to perform some elements of NOAA mission
			Growing reliance of NOAA on enterprise as partner for value-add and information dissemination
11	Workforce	NOAA will continue to rely on human capacity	Potential shortage of properly trained workers
			Proven value of training pathways and mentorship
			Inability to transition to new skill sets (Machine Learning, Deep Learning, software engineering, etc.)

12	Computing	Many NOAA capabilities depend on computing technologies	Growing reliance on and capability of cloud computing
			Hard-to-predict evolution of HPC
			Need to balance central processing unit (CPU) and graphics processing unit (GPU) capacity with storage and bandwidth
			Greater HPC investments by other nations and industry
13	Science	Key to advancing many NOAA capabilities	Expanding partnerships with other federal agencies
			Increasing need for international collaboration
			Scientific progress increasingly dependent on cross-disciplinary science - Earth system science and social and human behavioral sciences

Appendix IV. Priorities for Weather Research Recommendations

Observations and Data Assimilation		
Priority Area 1		Use and Assimilation of Existing Observations
OD-1		Maximize the use and assimilation of underutilized ground-based, airborne, and marine-based in situ, remote sensing, and crowd-sourced observations.
	OD-1.1	Develop a clear, well-defined process to stay informed of how NOAA instruments and data are being used outside of NOAA and explore integration of new observation systems that have been or are being developed by the private sector and in academia. The goal is to identify how they could be used most advantageously to advance NOAA's mission, and to streamline testing, evaluation, data assimilation, and use in NOAA research and operations.
	OD-1.2	Expand capabilities that provide support for testing observational strategies and capabilities from existing under-utilized ground-based observations identified above through funding collaborations between those who have developed or are developing the observational systems and those with expertise in data assimilation. Such effort will allow the observations to be assimilated most effectively in NWP.
	OD-1.3	Develop a clear, well-defined process to select and fund new observations for NOAA operations and have these observations ready for use in data assimilation systems.
	OD-1.4	Apply advanced and efficient data assimilation methods (see OD-3) for extreme precipitation prediction, icing, hydrologic and storm surge models, taking advantage of new networks of soil moisture, snowpack and snow level measurements, as well as novel airborne, ocean and satellite observations. Measuring forecast performance for extreme precipitation, streamflow and storm surge will help advance forecasts of these hazards. The next generation National Water Model (or system of regional models) is in development and could benefit from assimilation of these new observations now and in the future. Cost and benefit analysis should be performed to determine the optimal assimilation of such observations.
OD-2		Maximize the use and assimilation of underutilized satellite observations.
	OD-2.1	Prioritize resources to expand collaboration between NOAA, JCSDA, academia and other government agencies to perform research and development of satellite data assimilation and its operational transition, with JEDI as the open source to enable such collaboration.
	OD-2.2	Provide sustained support to improve fast radiative transfer models for all-sky and all-surface radiance data assimilation.
	OD-2.3	Provide sustained support to investigate methods to effectively assimilate satellite observations into NWP models (i.e., estimate satellite observation error and bias), and to investigate efficient methods to evaluate satellite observation impacts (e.g. Observing System Simulation Experiment (OSSE), Forecast Sensitivity Observation Impact).
	OD-2.4	Develop applications of novel satellite measurements for monitoring and prediction of coastal storm surge.
Priority Area 2		Advanced Data Assimilation Methods, Capabilities and Workforce

OD-3		Significant new support for novel methodology research and workforce development for data assimilation is necessary to establish and maintain state-of-the-science capabilities.
	OD-3.1	Establish a research program that is forward-looking and long-term (i.e., five years) to support innovative data assimilation methodology research across all spatial and temporal scales for weather and water, including the following eight topic areas: ● Novel use of artificial intelligence (AI) and machine learning (ML) in data assimilation ● Development of a multiscale data assimilation approach ● Development of data assimilation methods that account for nonlinearity and non-Gaussianity ● Development of methods to estimate observation errors, bias, cost-effective and accurate observation operator ● Development of a scalable and efficient data assimilation algorithms and systems ● Development of methods to represent or reduce numerical model error and bias using data assimilation ● Effective use of data assimilation to guide observation network design ● Creation of versatile data assimilation approaches for streamflow prediction using the National Water Model, and demonstration across a range of geographical and hydrological conditions
	OD-3.2	Create a university consortium to address critical research challenges for data assimilation and to foster a growing data assimilation workforce. Goals of this consortium should include: ● Tackling critical research issues for data assimilation through innovative research ● Increasing significantly the number of graduate students, especially Ph.D. students, in data assimilation ● Utilizing the modern software, Joint Effort for Data assimilation Integration (JEDI), developed by JCSDA to conduct data assimilation research and development to facilitate research to operations (R2O) ● Collaborating with NOAA to prioritize critical research areas in data assimilation (operations to research) ● Enabling an effective collaboration infrastructure (universities, NOAA labs and centers, JCSDA)
OD-4		Advance coupled Earth system data assimilation for weather, water, and sub-seasonal to seasonal forecasting.
	OD-4.1	Support the development of a workforce skilled in coupled data assimilation for weather, water, and S2S forecasting.
	OD-4.2	Invest in research and development on the assimilation of observations of the Earth system boundaries. It is crucially important to identify, represent, and reduce model errors at the Earth system component interface in a data assimilation framework.
	OD-4.3	Partnerships within NOAA, with other federal agencies (“the whole government”), universities and academia, private companies, and international operational centers should be established to make development of coupled data assimilation at all spatial and temporal scales a priority. JEDI is a unique framework for streamlining such collaboration and should be integral to this effort.
	OD-4.4	Support physical process studies involving coupling between major Earth system components using coupled data assimilation as tools.
	OD-4.5	Drastically reduce the data latency to improve operational coupled data assimilation.

OD-5		Advance the production of regional and global reanalyses.
	OD-5.1	Invest in reanalysis as a user-driven operational production and service in support of Earth science research, NWP forecast product development, climate services, and private sector applications.
	OD-5.2	Invest in research, with development and computing resources for global and regional reanalysis. Investments include improving input observations, leveraging and implementing NWP model and data assimilation research and development (FO-1, FO-2, OD-1 to OD-4), developing an optimal reanalysis configuration, and independent verification of the reanalysis. The service needs to rely on stable, dedicated resources including staff and HPC, but also leverage efforts from other agencies in the research and development and production of reanalysis.
	OD-5.3	Develop a continuous and comprehensive high-quality, multi-decade reanalysis that supports the use of AI and ML for the development and study of environmental scenarios.
	OD-5.4	Determine and establish an optimal life cycle for reanalysis that serves multiple purposes..
Priority Area 3		Observation Gaps and the Use and Assimilation of New Observations
OD-6		Develop and deploy a national boundary layer, soil moisture and smoke observing and data assimilation system for weather and sub-seasonal to seasonal prediction.
	OD-6.1	Develop a coordinated national profiling network over land with an offshore extension to routinely collect observations within the lower troposphere, observing the atmosphere from the ground up. Continuous profiling at high temporal frequency and vertical resolution is dictated by dominant temporal and spatial scales of processes within the PBL. To close the extant PBL observational gap, the proposed NOAA ground-based PBL observing network should be complemented by satellite, surface-based, and airborne measurements in a hybrid observing system.
	OD-6.2	Support collaborations between those designing and implementing the ground-based PBL system and those involved in data assimilation. The objective of these collaborations would be two-fold: to use data assimilation experiments to advance the design of the network, and to ensure that new observations can be assimilated immediately after the observational system testing and evaluation has concluded.
	OD-6.3	Support partnerships between NOAA, and the academic and private sectors, to design and implement such a national network and will help advance the NOAA mission.
	OD-6.4	Develop and deploy ground-based remote sensors that measure smoke plume insertion altitudes and its down-mixing and deposition to the surface and assimilate the data into numerical models. Develop and deploy airborne sensor packages to measure vertical profiles of smoke and aerosol concentrations and chemical makeup, by leveraging existing weather sensor and communication capabilities on commercial aircraft and their inherent ascent and descent flight patterns. Assimilate these observations into numerical models to improve wildfire prediction.
OD-7		Observe the ocean, its surface boundary layer, and ocean-atmosphere feedbacks, on weather space and time scales for seamless Earth system data assimilation and forecasting from minutes to years.

	OD-7.1	Complete, maintain and integrate existing ocean observing networks, and enhance existing ocean observing platforms with additional sensors (e.g., biogeochemical, salinity, currents, etc), to improve Earth system model forecasts and provide an integrated context for enhanced ocean boundary layer observations.
	OD-7.2	Leverage the expanding capabilities of the full community to design and build a nested ocean boundary layer observing system that can resolve the air-sea fluxes and inputs to their parameterizations to improve understanding and forecasts. Deploy instruments to measure the ocean and atmosphere transition layers and their covariances on weather space and timescales and analyze them with data-assimilating coupled models. Evaluate the forecast skill and evolve the observing system to maximize efficiency once the coupled models and data assimilation are sufficiently validated. Deploy an observing system that can maintain improved forecast skill.
	OD-7.3	Link these recommended major components for the ocean mixed layer to the atmospheric boundary layer recommendation. One focal point is the coastal regions, where a) the marine and continental layers meet and interact, b) the uncertainties in weather forecasting are particularly emphasized, and c) where weather events impact large human populations, marine ecosystems, marine transportation and offshore energy infrastructures. The system should also be linked with biogeochemical observations for managing ecosystems and forecasting coupled events such as harmful algal blooms in oceans and lakes.
OD-8		Leverage and expand atmospheric river (AR) observations to improve flood and drought prediction and to enable forecast-informed reservoir operations.
	OD-8.1	Implement a multi-phase program to improve the understanding and forecasting of ARs that leverages current and future aircraft, buoy, and satellite capabilities. The program should build upon existing capabilities and programs to expand coverage in space and time and improve forecasts through advanced data assimilation (OD-3), as well as integration of ocean surface and mixed layer observations (OD-7).
	OD-8.2	Adopt a research and operations partnership approach, including engagement of the international and academic communities.
	OD-8.3	The program development and implementation should create new forecast skill metrics targeting extreme precipitation prediction in the west and the phenomenon, ARs, that produces it. It should target socio-economic impact considerations including for use in reservoir operations to mitigate drought and flood impacts.
OD-9		Fill radar gaps using diverse weather radars and data assimilation.
	OD-9.1	NOAA should develop a clear, well-defined process to integrate more fully data from existing radars operated by others to complement NOAA ground based radars.
	OD-9.2	NOAA should begin deploying commercially available, low-cost C-band and X-band radars into areas in the western United Stateswhere NEXRAD gaps are most significant, and in the eastern United States where environmental justice analysis has found poor coverage from existing radars, with at least thirty radars deployed within three years.
OD-10		Prioritize smallsat/cubesat observation and data assimilation.
	OD-10.1	Develop robust smallsat/cubesat technology demonstrations.

	OD-10.2	Establish a capability to develop, test and implement new data assimilation methods tailored to using smallsat/cubesat measurements (e.g., via collaboration with the academic community).
Forecasting		
Priority Area 1		Foundational Earth System Modeling.
FO-1		Accelerate Earth system model development and seamless prediction.
	FO-1.1	As ESMs mature, modeling for prediction at lead times of hours to years should move toward ESMs, with model-prognostic components for all Earth components, including the atmosphere (including aerosols), land surface, oceans, and sea ice, that are coupled for both data assimilation and forecasting (see Box 2 in Section 5.2). That is, the current GFS and planned seasonal forecast system (SFS) should advance to become full ESMs.
	FO-1.2	Focus Earth system model development on appropriate and consistent performance metrics that align with stakeholder needs.
	FO-1.3	Facilitate research to operations (R2O) for seamless prediction by adopting a unified ESM, including accurate BGC cycles of carbon and nitrogen, with coupled data assimilation, ensemble, and downscaling refinement capabilities for all forecasting applications.
	FO-1.4	Mesoscale-resolving ESMs (less than five kilometer grid spacing in all components) should be developed and implemented into operations by 2030, with subgrid-scale uncertainty represented by machine-learning-based stochastic parameterizations.
	FO-1.5	An open development framework should be employed, including data assimilation, initialization, forecast, post-processing and statistical modeling. Investments should be made to enable ESMs to take advantage of the rapidly changing high performance computing architecture and software engineering advances (see FE-7).
FO-2		Achieve the best possible operational numerical weather prediction at all time scales.
	FO-2.1	Having the best possible operational NWP is foundational to meeting the overall NOAA mission and maximizing the nation's resilience to adverse weather and a changing climate. To achieve this, it is recommended that NOAA commits to creating the best possible operational NWP within a framework that includes: ● A realistic, yet aggressive strategic plan and program focused on this objective that includes explicit metrics, activities, investments, and milestones. ● A process by which Congress and the Nation routinely assesses and holds NOAA accountable to execute those plans and achieve the goal. ● Significant new research investments in the entire spectrum of science needed for world-class operational NWP, including coupled Earth-system science and modeling, model physics, data assimilation, ensembling, post-processing and AI technologies, all under the framework of the UFS ● Initiatives such as the Earth Prediction Innovation Center (EPIC) that support and incentivize external partners to conduct NWP modeling research and development in a manner that contributes to the NWP excellence goal.
	FO-2.2	Acquire substantially more computing power to support the research, development, testing and implementation of a world class NWP portfolio (see FE-6). A majority of the new computer resources should be allocated to research and development within NOAA and across the broader weather research community.

	FO-2.3	In conjunction with other relevant federal agencies such as the National Science Foundation (NSF), catalyze a substantial increase in the pipeline of next-generation researchers, technicians, and practitioners trained to advance the requisite and complex modeling, observation, assimilation, and computing science and technology. This could be accomplished by enhancing and catalyzing institutions, programs and other initiatives that can teach these disciplines. NOAA should make dedicated modeling, data and computing platforms available to support such programs.
FO-3		Establish a regular, sustained Earth system reforecasting activity to enable a more effective cadence of operational model improvements.
	FO-3.1	Invest in reforecasting as a user-driven operational production and service in support of Earth science research, NWP forecast product development, and private sector applications.
	FO-3.2	Invest in research and development to advance reforecasting.
	FO-3.3	Determine the optimal configuration and cadence of reanalysis, reforecasting and operational implementations that can provide the best framework for model development and climate monitoring.
Priority Area 2		Advancing Critical Forecasting Applications
FO-4		Enhance prediction of Earth's water cycle extremes to achieve integrated water cycle modeling.
	FO-4.1	Elevate the evaluation of water-cycle related variables including: precipitation analysis and forecasting; flood discharge and inundation; drought intensity, duration, and area; and water quality.
	FO-4.2	Improve coordination among the multitude of intersecting efforts that set research priorities and correspondingly fund research related to the water cycle.
	FO-4.3	Use a scientifically-vetted, supported, community water modeling framework and data assimilation systems in operational forecasting of water quality and quantity. Require benchmarking of forecast models with an open, transparent approach that supports code contributions and testing within two weeks.
	FO-4.4	Make major, sustained investment in water data assimilation capabilities to accelerate the use of more water observation information and improve forecast product skill.
	FO-4.5	Expand research to address scientific issues and uncertainties in model process coupling (i.e., compound flooding such as coastal-riverine-pluvial flooding, surface-groundwater coupling, land-atmosphere coupling). Model coupling is not just a software issue but is a significant science challenge.
FO-5		Substantially increase the level of effort to advance predictive capabilities for fire weather and air quality.
	FO-5.1	Develop a comprehensive, coupled, ensemble-based Earth system model capable of hourly to seasonal prediction of atmospheric composition and AQ. The Earth system approach is fundamental to improved AQ forecasts, supplying accurate boundary conditions and initializations and the necessary coupling to land and water surfaces.

	FO-5.2	Advance the use of ML to realize model efficiencies and thereby facilitate high-resolution and ensemble approaches needed to produce forecasts at the required spatial scales.
	FO-5.3	Leverage and support interagency partnerships in model development and evaluation. This includes expansion of interagency cooperation via sharing of updated emissions inventories and codes and co-development of schemes for data assimilation.
	FO-5.4	Provide additional computational resources for AQ and fire weather model research, development, and evaluation. The computational demands are large but are justified by the importance of these applications in protecting people and property and the need to accelerate progress.
FO-6		Commit to improving forecasts of high-impact weather through multi-sector partnerships, in concert with the Earth Prediction Innovation Center program.
	FO-6.1	Take a comprehensive approach to improving understanding and conceptual models of HIW phenomena.
	FO-6.2	Work with partners within the UFS framework to develop sophisticated regional and nested models with enhanced model physics to increase their predictive skill in the ESM suite, and to improve techniques for ensemble generation and their applications to HIW events. As the ESM matures, there should be a careful assessment of whether separate stand-alone hurricane and water models add value to the production suite, with awareness of how ESM output is used by the community in other modeling systems.
	FO-6.3	Make the NWS Warn-on-Forecast (WoF) vision (see Box 3 in Section 5.3) a high priority and extend it to other HIW phenomena in concert with the Forecasting a Continuum of Environmental Threats (FACET) program.
	FO-6.4	Work with forecasters and social, behavioral, and economic scientists on innovative diagnostic and guidance products and effective communication of risks and impacts.
	FO-6.5	Involve the external community via the EPIC program and extramural funding opportunities. NOAA should proactively ensure the success of EPIC by encouraging coordination and collaboration among all its relevant programs (e.g., Environmental Modeling Center (EMC), Weather Program Office (WPO), Office of Science and Technology Integration (OSTI), Developmental Testbed Center (DTC) and relevant OAR laboratories and Cooperative Institutes) with EPIC and the Weather Enterprise.
FO-7		Advance research on coastal processes in Earth system models to achieve comprehensive coastal modeling.
	FO-7.1	Support the following important areas for coastal modeling research: a) total water level, including the effects of ocean currents and structure, tides, surge, waves and overtopping and overtopping, and fluvial and pluvial water sources to benefit decisions related to flooding and other weather-related hazards in the coastal zone, (contributions needed in ESS, MD, DC) and b) nearshore processes, particularly morphological modeling, air-sea-wave coupling, and physical-biogeochemical coupling to benefit decisions concerning weather-related hazards and water quality, including harmful algal blooms, in the coastal zone (contributions needed in ESS, MD, DC).
	FO-7.2	Support research needed to make models more useful for forecasting including: a) model performance optimization for new computational platforms (contributions needed in MD,

		HPC); b) ensemble and probabilistic modeling with error metrics (contributions needed in ESS, DS); c) the expanded use of explainable AI and ML (contributions needed in ESS, MD, and DS).
Information Delivery		
Priority Area 1		Highly Reliable, High-resolution (HR2) Weather Information Dissemination, with Inclusive and Open Science to Maximize Societal Benefits
ID-1		Embrace open science.
	ID-1.1	Develop and maintain highly available and disaster-proof data-access portals that are operationally supported (i.e., 24/7/365) to provide all NOAA weather and climate forecast and observational data in industry-recognized formats (e.g., Network Common Data Form (NetCDF), GeoJSON, etc.). ● These operational portals should be scalable and maintainable to meet the needs of public and private partners, completed within two years, and continuing for the next ten years. ● Data availability should be structured such that users subscribe for access to published information. ● Should include SLA and establish long-term contracts with explicit requirements and strong guarantees for operational information delivery, and second-tier SLAs for archived, historical, and research data that have reduced requirements.
	ID-1.2	Create an open science consortium that includes private commercial and nonprofit partners, academia, and the open science community to coordinate activities in response to the 2021 draft UNESCO Recommendations on Open Science[56] and recent National Academies reports.[37-38] This consortium should a) normalize open science for the next generation of scientists that will participate in NOAA's Weather Enterprise, b) accelerate science by motivating and supporting the science community's move towards open science, and c) broaden participation in NOAA's Weather Enterprise and reduce barriers (see Section 7.3). This could include, for example: ● In collaboration with the broader weather community, establish consistent and open data standards to support open science; simple, general, cloud-optimized data formats and Application Programming Interfaces (API) that support accessibility, usability, and preservability throughout the Weather Enterprise, and simplify R2O ● Partner with other agencies (i.e., National Aeronautics and Space Administration (NASA), United States Space Force (USSF), FAA, United States Forest Service (USFS), United States Geological Survey (USGS)) to collocate data with high joint utility and to support a transition to cloud architectures ● Partner with other community science groups, working to preserve and protect our natural resources ● Build the community by creating summer schools, internships, conferences around open science, citizen science, and environmental justice ● Create open information tools for searching and analyzing data and publications, and tracking origin, provenance, and trust ● Develop methods for the deployment of algorithms, i.e., new methods for reanalysis, or new algorithms for processing large data sets (e.g., multi-radar multi-sensor (MRMS) data) {See Recommendation OD-3}
ID-2		Within two years, implement the existing plan to address NWS operational data dissemination challenges by leveraging content delivery networks and accelerating the migration to commercial cloud networks.

	ID-2.1	Leverage content delivery networks and accelerate migration to the cloud.
	ID-2.2	Prioritize retention of expertise in software, data, and networking within NOAA and NOAA contractors to address limitations and ensure future innovation.
ID-3		Create a NOAA-wide function to provide Weather Enterprise data integration and dissemination strategy and operational oversight.
	ID-3.1	Create robust coordination and collaboration frameworks that ensure effective dissemination and sharing of pertinent NOAA data, including addressing outdated dissemination methods, to the public sector (i.e., interagency) and private sector partners. These frameworks should address all sectors (e.g., aviation, shipping, roads, utilities, etc.) and hazards (e.g., severe, tropical, fire, winter, air quality, flooding, etc.).
	ID-3.2	Research should be undertaken to understand the full extent of NOAA data utilization, especially across federal agencies and large commerce sectors, to better design and establish these frameworks.
	ID-3.3	Ensure that there is coordination across agencies and partners (e.g., NOAA, FAA, DoD, universities, etc.) to eliminate duplication of efforts and maximize research talent and funding.
	ID-3.4	Prioritize research and frameworks focusing on fire weather and aviation within NOAA and across partner agencies, the private sector, and universities to address significant research and operational knowledge and data gaps.
Priority Area 2		Promote an Ongoing Virtuous Cycle of Collecting Social, Behavioral, and Interdisciplinary Observations, and Assimilating and Analyzing the Data to Improve Weather information Delivery
ID-4		Prioritize and integrate inter- and trans-disciplinary research on equitable and effective use of hazardous weather information.
	ID-4.1	Examine for whom, in what hazard scenarios, when, and how forecast uncertainty (probabilistic) information is advantageous versus when it is not, including whether and when it's potentially detrimental. Consider characterization, communication, and use of both forecast uncertainty and forecast confidence. Prioritize research on hazard scenarios exacerbated by climate change (e.g., fire weather, drought, heat, extreme precipitation and flooding, winter storms).
	ID-4.2	Examine how to more effectively convey information visually, in a geospatial context (e.g., interaction modes, geographic contents, resolution, symbols and color selections, and semiotic principles), with a focus on how representations of the weather hazard (including uncertainty and scenario-based forecasts) combined with other information (e.g., infrastructure, landmarks, locations of supplies or shelters) can improve risk assessment and decision-making.
	ID-4.3	Characterize and address issues of weather information inequity. Consider community-centered approaches to situate the research in particular cultures, populations, and resources. Research should include studying: a) information access (e.g., for non-English-speaking, deaf, people with hearing loss, visually impaired, etc.), b) geographic areas with poor infrastructural (cellular, internet, radar) coverage), c) protective response options (i.e., shelters, and time-to-reach them for those in manufactured housing), and d) potential mediators and/or moderators of these, such as social support and trust.

	ID-4.4	Identify the circumstances (e.g., hazard type, region, season, etc.) in which automated guidance, including NWP-based guidance (deterministic, ensemble, and “blended” guidance) and AI- and ML-based guidance, does and does not work. Such research should consider hazard predictability limitations, trust in the guidance by users (including forecasters and end-users), NWS partners’ IDSS needs, and failure implications.
	ID-4.5	Conduct research on characterizing and communicating impacts of weather hazards, leveraging diverse data sources (e.g., traffic, retail purchases, infrastructure data layers, social media data) and potential AI and ML techniques. Such research must consider the predictability and prediction capabilities of impacts across scales and contexts. Conduct research to consider and clarify the capabilities of NOAA to communicate these impacts—perhaps depending on the type and scenario of the hazard (e.g., feasibility for rapidly-evolving weather hazards, like tornadoes, flash floods, wildfires)—versus in partnership with other public agencies (e.g., emergency personnel) and the private sector (see ID-6).
ID-5		In collaboration with researchers working on Recommendation ID-4, NOAA should partner with other agencies and the private sector to develop, test, and evaluate probabilistic and deterministic hazard information delivery capabilities for a broad spectrum of end-users.
	ID-5.1	Expand and strengthen relationships across academic, private and government sectors to allow rapid information exchange between research results and dissemination strategies to ensure that the most useful products have viable dissemination pathways.
	ID-5.2	Coordinate organizational and geographical collaborations of NWS offices and centers with partner agencies, in social-functional networks, to optimize weather information flows through partner agencies’ operational procedures. Social-functional network research could help formalize core aspects of IDSS, including their implementation through InteractiveNWS (iNWS), Integrated Realtime Impact Services (IRIS), and the IDSS management system (IMS) to enhance the value of and go beyond personal connections across agencies, increase mutual awareness of weather information availability and use, and promote preserving and sharing knowledge and experiences. This will require addressing Recommendations ID-1 and ID-2 above, to address capacity issues.
ID-6		Build capacity to develop multi-dimensional metrics, data repositories, and new data collection methods and standards for “baseline” data (i.e., not event-specific) and for event-specific “perishable” social and behavioral data.
	ID-6.1	Metrics development efforts: a) require research to define the suite of relevant and meaningful outcome variables (i.e., dependent variables, predictands) to measure, particularly for mission-critical themes (e.g., effective IDSS, effective risk communication, etc.), b) should not be static but need to evolve to incorporate new measures over time, c) must take care not to generalize findings beyond what is valid (e.g., populations, hazards, scenarios, measures, etc.
	ID-6.2	Particular effort should be given to support real-time collection of data for specific weather hazards when they are threatening. While such data are notoriously difficult to collect, they are highly useful, and it is important for resources to be provided to develop a plan for gathering these observational data. Such knowledge is essential for understanding how people are accessing and interpreting forecast information, assessing their risk and evaluating options, and making protective decisions.
	ID-6.3	Consistent with open and transparent science initiatives outlined above, encourage publication of social and behavioral science data collection instruments (e.g., surveys, experimental design, interview protocols) and, as allowable per policies protecting human subjects, datasets.

Foundational Elements		
Priority Area 1		Science
FE-1		Develop a weather-knowledge ecosystem.
	FE-1.1	Build capacity to develop multi-dimensional metrics, data repositories, and new data collection methods and standards for “baseline” (i.e., not event-specific) and event-specific “perishable” social and behavioral data, particularly for perishable data in the predictive phase of a threat—which poses methodological challenges—as well as in the aftermath.
FE-2		Continue to invest in understanding the basic physics, chemistry, and dynamics of the Earth system
	FE-2.1	Increase direct support of critical research topics, in partnership with other federal and international agencies engaged in these topics, and catalyze the existing robust community of Earth system scientists to adopt and advance NOAA technologies (e.g., UFS and JEDI) as the preferred research and development platforms through EPIC and similar community initiatives.
FE-3		Accelerate the NOAA AI strategy and expand efforts in data aggregation, scientific research and social science for AI
	FE-3.1	Establish accurate, high-quality, historical AI-ready datasets including observational data, analysis, and model output and make them available through open science platforms that allow all researchers and communities to collaborate, supporting diversity and environmental justice.
	FE-3.2	Develop multi-agency cooperation around data sharing on open science platforms with common, open, cloud-optimized data standards.
	FE-3.3	Develop research in physics-based AI, hybrid NWP, explainable AI, and robust AI, and uncertainty quantification.
	FE-3.4	Create interdisciplinary teams of AI researchers, social scientists, and meteorologists, climate scientists, ocean scientists and more, focusing on risk communication and the creation of trustworthy systems.
FE-4		Increase university involvement in NOAA research.
	FE-4.1	Investment options to consider include: ● significant increase in external grants funded through the WPO with an open-ended grants submission process; ● pattern the review processes after those used by NSF; fund research over a broader range of readiness levels; employ a temporary program director as done by NSF (“rotators”) to enhance professional networks at NOAA; emphasize diversity, equity, and inclusion in proposal requirements; ● grant durations of three to five years to support graduate students with a focus on those working on a PhD; early career grants to young tenure-track university faculty members; emphasize special areas of need as determined by NOAA.
	FE-4.2	High performance computing resources must be provided to engaged researchers as needed to make sure grant projects can be successful.
FE-5		Create multi-university research consortiums to address critical research issues for NOAA

	FE-5.1	The first NOAA consortium should be focused upon data assimilation as a critical need for NOAA. There is no federal agency that directly funds basic research in data assimilation, yet the need is great and experts in this area are defined as a critical NOAA workforce need.
	FE-5.2	Support a robust, thriving, interdisciplinary and convergent weather information development and delivery research program in partnership with other public and private research organizations.
	FE-5.3	Advance open science efforts to deliver user-oriented weather forecast information for dynamic, interacting weather hazards, and social and technological systems.
Priority Area 2		Computing
FE-6		The federal government should immediately invest in substantially more computing resources dedicated to weather forecasting research, development, testing and operations, and demonstrate a long-term intent to sustain the United States as the leader in computing technology and resources for weather.
	FE-6.1	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 UFS.
	FE-6.2	The open science and community engagement recommendations elsewhere in this report require weather enterprise access to lower security HPC assets that are not constrained by the expense and security requirements of operational assets.
	FE-6.3	Owing to transport limitations, an increasingly larger portion of value-added data processing should be done within the HPC computing facilities by both NOAA and weather community users in order to allow the nation to take full advantage of NOAA data.
	FE-6.4	The investments should be balanced across all aspects of computing, including data storage, access and transport.
	FE-6.5	Immediately undertake a study to determine the full computing needs of the weather research and operations community, including that of its research partners, and report to Congress the results.
FE-7		NOAA must immediately invest in long-term programs to convert, prepare for, and leverage new and emerging high performance computing architectures such as cloud, graphics processing units, exascale and quantum.
	FE-7.1	Refactor the UFS to leverage emerging technologies.
	FE-7.2	Invest in a paradigm and 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.
Priority Area 3		Workforce Development

FE-8		Develop a pipeline of diverse talent from K-12 students to undergraduate and graduate students to NOAA employees to lifelong learning and professional development.
	FE-8.1	NOAA and other federal agencies (NSF, U.S. Department of Education, etc.) should invest in programs to develop a pipeline of next- generation researchers, engineers, and practitioners that are skilled in and can operate or develop weather technologies that exploit and advance emerging computing architectures, data assimilation programs and observing systems. This includes catalyzing academic partners to develop programs for all levels of students (undergraduate through post-doctorate) as well as programs to educate the existing workforce in NOAA, academic and private sector institutions.
	FE-8.2	Be opportunistic to entrain the best international talent into NOAA.
FE-9		Develop an enterprise vision for workforce education and training at multiple degree levels that is flexible enough to accommodate different line office needs and leverage existing resources available to the community.
	FE-9.1	NOAA should establish employee professional training programs in needed areas of expertise (e.g., cloud and emerging new HPC computing technologies, open source code development, AI and ML, data assimilation, instrumentation) to increase retention and remain agile amidst technological change.
	FE-9.2	Eliminate gaps in expertise through partnering, enabling NOAA resources to be focused on innovation and applications rather than replication.
Priority Area 4		Weather Enterprise
FE-10		Create a NOAA-wide function to provide Weather Enterprise data integration and dissemination strategy and sustained operational oversight to ensure preparedness and response.
	FE-10.1	Invest to ensure availability and continuity of data and information across NOAA, including ingest and egress from, and to, all appropriate participants across the Weather Enterprise, to improve weather data, modeling, computing, forecasting and decision support, including severe weather warnings.
	FE-10.2	Invest to implement EISWG Data Dissemination report[36] Recommendations 3 and 4 to leverage content delivery networks and accelerate migration to commercial cloud networks for all integration and dissemination of NOAA weather-related information across the Weather Enterprise for societal benefits.

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Appendix VI. Acronyms

AI/ML = artificial intelligence/machine learning
AMS = American Meteorological Society
API = application programming interface
AQ = air quality
AR = atmospheric river
AWIPS = Advanced Weather Interactive Processing System
BDP = Big Data Program
BGC = biogeochemistry
CFS = Climate Forecast System
CI = Cooperative Institute
CONUS = Continental United States
CPC = Climate Prediction Center
DC = data collection
DOD = Department of Defense
DOE = Department of Energy
DS = data science
DTC = Developmental Testbed Center
ECMWF = European Centre for Medium-Range Weather Forecasts
EF = Enhanced Fujita
EISWG = Environmental Information Services Working Group
EMC = Environmental Modeling Center
EPA = Environmental Protection Agency
EPIC = Earth Prediction Innovation Center
ESM = Earth System Model
ESS = Earth system science
FAA = Federal Aviation Administration
FACETs = Forecasting a Continuum of Environmental Threats
FAIR = findable, accessible, interpretable, and reusable
FE = Foundational Elements
FFRDC = federally funded research and development centers
FO = Forecasting
FTAC = Fast-Track Action Committee
GFS = Global Forecast System
GOMO = Global Ocean Monitoring and Observing
GOOS = Global Ocean Observing System
GPRA = Government Performance and Results Act
GPU = graphics processing unit
GSD = Global Systems Division
HF = high frequency
HFIP = Hurricane Forecast Improvement Program

HIW = high-impact weather
HPC = high performance computing
HR2 = highly reliable, high-resolution
ICAMS = Interagency Council for Advancing Meteorological Services
ID = Information Delivery
IDSS = impact-based decision support services
IMS = IDSS management system
iNWS = Interactive NWS
IOC = Intergovernmental Oceanographic Commission
IOOS = Integrated Ocean Observing System
IPCC = Intergovernmental Panel on Climate Change
IRIS = Integrated Realtime Impact Services
JCSDA = Joint Center for Satellite Data Assimilation
JEDI = Joint Effort for Data assimilation Integration
MD = model development
MRMS = multi-radar, multi-sensor
NASA = National Aeronautics and Space Administration
NCAR = National Center for Atmospheric Research
NCEP = National Centers for Environmental Prediction
NESDIS = National Environmental Satellite, Data, and Information Service
NetCDF = Network Common Data Form
NEXRAD = Next Generation Weather Radar
NIDIS = National Integrated Drought Information System
NMFS = National Marine Fisheries Service
NOAA = National Oceanic and Atmospheric Administration
NOS = National Ocean Service
NSF = National Science Foundation
NST = NOAA Support Team
NWC = National Water Center
NWP = numerical weather prediction
NWS = National Weather Service
OAR = Oceanic and Atmospheric Research
OD = Observations and Data Assimilation
OMAO = Office of Marine and Aviation Operations
OSTI = Office of Science and Technology Integration
OSTP = Office of Science and Technology Policy
PBL = planetary boundary layer
PF = peta floating point operations per second
PWR = Priorities for Weather Research
R2O = research to operations
R2O2R = research to operations to research
RAOP = Research And Operations Partnership
RA/RF = reanalysis/reforecast

RL = readiness level
S2S = Subseasonal to Seasonal
SAB = Science Advisory Board
SBN = satellite broadcast networks
SLA = service level agreement
SME = Subject Matter Expert
UFS = Unified Forecast System
UNESCO = United Nations Educational, Scientific, and Cultural Organization
USACE = U.S. Army Corps of Engineers
USAF = U.S. Air Force
USDA = U.S. Department of Agriculture
USFS = U.S. Forest Service
USGS = U.S. Geological Survey
USSF = U.S. Space Force
UxS = uncrewed systems
WCOSS II = Weather and Climate Operational Supercomputing System II
WFO = weather forecast office
WMO = World Meteorological Organization
WoFS = Warn-on-Forecast System
WPO = Weather Program Office
WRN = Weather-Ready Nation
WRFIA = Weather Research and Forecasting Innovation Act of 2017

Appendix VII. Glossary

Air quality: A reference to the degree to which the ambient air is pollution-free, assessed by measuring a number of indicators of pollution.

Artificial intelligence: The theory and development of computer systems able to perform tasks that normally require human intelligence, such as visual perception, speech recognition, decision-making, and translation between languages.

Atmospheric river: A long, narrow, and transient corridor of strong horizontal water vapor transport that is typically associated with a low-level jet stream ahead of the cold front of an extratropical cyclone. The water vapor in atmospheric rivers is supplied by tropical and/or extratropical moisture sources.

Billion-dollar weather and climate disasters: Defined and tracked annually by NOAA's NCEI; it includes weather climate events for which overall damages/costs reached or exceeded $1 billion (including CPI adjustment to 2021).

Citizen science: The collection and analysis of data relating to the natural world by members of the general public, typically as part of a collaborative project with professional scientists.

Climate change: Any systematic change in the long-term statistics of climate elements (such as temperature, pressure, or winds) sustained over several decades or longer. Climate change may be due to natural external forcings, such as changes in solar emission or slow changes in the earth's orbital elements; natural internal processes of the climate system; or human caused.

Cooperative institutes: NOAA Cooperative Institutes are academic and non-profit research institutions that demonstrate the highest level of performance and conduct research that supports NOAA's Mission Goals and Strategic Plan.

CubeSat: A class of research spacecraft called nanosatellites. CubeSats are built to standard dimensions (Units or "U") of 10 cm x 10 cm x 10 cm. They can be 1U, 2U, 3U, or 6U in size, and typically weigh less than 1.33 kg (3 lbs) per U.

Cybersecurity: Cyber security is the practice of defending computers, servers, mobile devices, electronic systems, networks, and data from malicious attacks.

Data assimilation: The combining of diverse data, possibly sampled at different times and intervals and different locations, with short-range model forecasts, into a unified and consistent description of a physical system, such as the state of the atmosphere.

Download and upload process: Downloading is the transmission of a file or data from one computer to another over a network, usually from a larger server to a user device. Download can refer to the general transfer of data or to transferring a specific file. Uploading is the transmission of a file from one computer system to another, usually-larger computer system.

Earth system: Earth´s interacting physical, chemical, and biological processes, including humans and their impacts. The system consists of the land, oceans, atmosphere and polar regions. It includes the planet’s natural cycles -- the carbon, water, nitrogen, phosphorus, sulfur and other cycles.

Earth system model: An Earth system model (ESM), as used in this report, is a mathematical model of all the important 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.

Environmental justice: Environmental justice is the fair treatment and meaningful involvement of all people regardless of race, color, national origin, or income, with respect to the development, implementation, and enforcement of environmental laws, regulations, and policies.

Equitable access: the assurance that a warning system works for and is available to every single person, independent of language, preferred social media outlets, and infrastructure expansion.

Exa floating point operations per second (FLOPS): 10^{18} FLOPS, which is a measure of compute performance used to quantify the number of floating-point operations a core, machine, or system is capable of in a one second.

Explainable artificial intelligence / machine learning: Explainable AI/ML means that the results can be understood by humans (e.g., domain experts), in contrast to a situation where it is not clear how or why an AI algorithm yielded a particular result.

Fire weather: Weather variables, especially wind, temperature, relative humidity, and precipitation, that influence fire initiation, intensity, spread and suppression.

Floating point operation: a floating-point operation is any mathematical operation (such as +, -, *, /) or assignment that involves floating-point numbers (as opposed to binary integer operations).

Fluvial water: Stream-related processes are called fluvial (from the Latin word fluvius = river). Water in such processes dislodges, dissolves, or removes surface material in the process called erosion. River systems, fluvial processes and landscapes, floodplains, and river control strategies are important to human populations.

Forecasting: A process intended to calculate or predict (some future event or condition) usually as a result of study and analysis of available pertinent data using statistical, numerical, or other methods.

Geospatial metadata: Geospatial metadata describes maps, Geographic Information Systems (GIS) files, imagery, and other location-based data resources

Global Forecast System (GFS): NCEP's operational global forecast model. The GFS is run four times daily, with forecast output out to 384 hours.

High-impact weather: Weather events have social and economic impacts. They affect our food and water supply, damage our infrastructure, and put public health at risk.

High performance computing: Refers to the practice of aggregating computing power in a way that delivers much higher performance than one could get out of a typical desktop computer or workstation in order to solve large problems in science, engineering, or business.

Impact-based Decision Support Services (IDSS): IDSS are forecast advice and interpretative services the NWS provides to help core partners, such as emergency personnel and public safety officials, make decisions when weather, water and climate impacts the lives and livelihoods of the American people.

Information delivery: Information Delivery is the act of conveying information from one person to the other or from one place to the other.

Machine learning: Machine learning is a branch of artificial intelligence (AI) and computer science which focuses on the use of data and algorithms to imitate the way that humans learn. It includes the use and development of computer systems that are able to learn and adapt without following explicit instructions, by using algorithms and statistical models to analyze and draw inferences from patterns in data.

Mesoscale: Pertaining to atmospheric phenomena having horizontal scales ranging from a few to several hundred kilometers, including thunderstorms, squall lines, fronts, precipitation bands in tropical and extratropical cyclones, and topographically generated weather systems such as mountain waves and sea and land breezes.

Mission critical mile: This is used in this PWR Report to characterise the combination of understanding audiences (the “first mile”) and delivery of weather information to those audiences (the “last mile”).

Mission Service Area (MSA): An MSA is a NOAA core function that is focused on a specific environmental process, socioeconomic sector or activity to achieve societal outcomes aligned with NOAA’s mission.

Numerical weather prediction: Numerical weather prediction (NWP) uses mathematical models of the atmosphere and oceans to predict the weather based on current weather conditions.

Observations: Atmosphere observation refers to all equipment and techniques used to study properties of the atmosphere, including temperature, pressure, air movements, and chemical composition. Observations can be taken in situ or remote (e.g., satellite).

Open science: Open Science is frequently defined as an umbrella term that involves various movements aiming to remove the barriers for sharing any kind of output, resources, methods or tools, at any stage of the research process. As such, open access to publications, open research data, open source software, open collaboration, open peer review, open notebooks, open educational resources, open monographs, citizen science, or research crowdfunding, fall into the boundaries of Open Science.

Overtopping: Overtopping flow occurs when a water detention structure's capacity is surpassed and flow passes over the structure. Potential sites of overtopping flows are embankments such as dams, levees, detention basins, etc.

Peta floating point operations per second: 10^{15} FLOPS, which is a measure of compute performance used to quantify the number of floating-point operations a core, machine, or system is capable of in a one second.

Planetary boundary layer: The bottom layer of the troposphere that is in contact with the surface of the earth. It is often turbulent and is capped by a statically stable layer of air or temperature inversion.

Pluvial: Pertaining to rain, or more broadly, to precipitation, particularly to an abundant amount thereof.

Priorities for Weather Research Strategic Framework: The three principal pillars of the weather information development and delivery system (observations and data assimilation, forecasting, and information delivery) and their underlying foundational elements (science, computing, workforce development and the Weather Enterprise) that support the overarching goals of saving lives and property, fostering a vibrant weather-informed economy, and achieving equity in the development and delivery of weather information.

Readiness level: A Readiness Level (TRL) designation is to measure the maturity of technology components for a system. The measurement allows project stakeholders an understanding of how much development a certain technology needs before being utilized or put into production.

Reanalysis: A meteorological and climate data assimilation project which aims to assimilate historical atmospheric observational data spanning an extended period, using a single consistent assimilation (or "analysis") scheme throughout.

Reforecast: These are retrospective weather forecasts generated from reanalyses and a fixed or frozen numerical model. Model developers use them for diagnosing model bias and other characteristics, thereby facilitating the development of new, improved versions of the model.

Research to operations to research (R2O2R): This refers the the interplay between research and operations. Collectively, there is a continuum of closely linked activities, in a feedback loop with one leading to the other – research to operations to research and so on.

Smallsat: A small satellite, miniaturized satellite, or smallsat is a satellite of low mass and size, usually under 500 kg (1,100 lb). While all such satellites can be referred to as "small," different classifications are used to categorize them based on mass. Satellites can be built small to reduce the large economic cost of launch vehicles and the costs associated with construction.

Sub-seasonal to seasonal (S2S): The S2S time scale refers to forecast lead times ranging from two weeks to two years.

Virtuous cycle: A virtuous cycle is a chain of events in which one desirable occurrence leads to another which further promotes the first occurrence and so on resulting in a continuous process of improvement

Warn-on-Forecast: Warn-on-Forecast is a National Oceanic and Atmospheric Administration research project that aims to increase lead time for tornado, severe thunderstorm, and flash flood warnings.

Weather-knowledge ecosystem: The complex network and collaborative infrastructure of the Weather Enterprise that represents the portfolio of scientific assets available for the enhancement and expansion of weather services.

Weather-Ready Nation: Weather-Ready Nation (WRN) is a strategic outcome where society’s response should be equal to the risk from all extreme weather, water, and climate hazards.

Weather Research and Forecasting Innovation Act of 2017 (WRFIA): The Weather Research and Forecasting Innovation Act of 2017 (the Weather Act) bolsters the Office of Oceanic and Atmospheric Research's (OAR) commitment to advancing weather research and reinvigorating the weather portfolio. The Weather Program Office (WPO) ensures alignment of office practices with the strategic goals outlined in the Weather Act. This includes collaborating with various subject matter experts across NOAA to develop Congressional reports and deliverables required by the Weather Act, and briefing NOAA leadership on OAR-related activities and reports.

Weather Enterprise: The Weather, Water, and Climate Enterprise, also known as the Weather Enterprise for short, comprises three main sectors that contribute to the science of weather and weather forecasting -- academia, government, and America's Weather Industry.