

Extended Outline

# Priorities for Weather Research

NOAA Science Advisory Board

August 2021

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## Section 1: Charge from the U.S. Congress

[Language](#) from the FY21 Omnibus Appropriations Bill, Book 1, page 232:

**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.

## **Section 2: Executive Summary (for Policy Makers)**

NOTE: The Executive Summary will be completed following the first draft of the report. It will contain:

- Overview of Purpose and Crucial Importance.
- Summary of External World - Overarching trends, environmental equity, risks, opportunities.
- Summary Findings & Recommendations from Section 5
  - Includes a link to summary table of recommendations
- Summary Immediate Priorities and Common Challenges
- Summary Suggestions for Follow Up

## Section 3: Introductory Sections

### *The Growing Urgency for Weather Information*

- Billion Dollar (or greater) Weather and Climate Disasters (tropical cyclones, severe storms, drought, flooding, wildfires, winter storm, freezes) are tracked in NOAA's National Centers for Environmental Information (NCEI) database
  - Over the last 40 years, the U.S. has experienced nearly 300 "Billion Dollar Disaster" events that have caused nearly \$2 Trillion in damage and resulted in nearly 15,000 deaths.
  - The number of "Billion Dollar Disasters" per year is increasing, with an average of 5 per year over the first 30 years increasing to 14 per year over the most recent 10 years.
  - In 2020 alone, damage from 22 "Billion Dollar Disasters" totaled \$100 billion.
- The U.N.'s Intergovernmental Panel on Climate Change (IPCC) scientific consensus (August 2021) 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. The accelerating climate crisis will be with us for decades as the U.S. and other national governments develop the policies, technologies and science-based actions required to change global climate trends.
- Water, food, energy, and national security, as well as economic prosperity, are increasingly linked to the weather, and to the increasing weather variability and extremes that are increasingly traced to climate change. This expands the need for more accurate and tailored forecasts of environmental conditions on time scales ranging from minutes to seasonal to decadal.
- The U.S.'s 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 & technological advances, leverage the vast capabilities of the Weather Enterprise, and together, expand and deliver the foundational core products and services our nation requires for weather, water and climate resiliency, and economic prosperity.

### *NWS Mission, Vision and Mission Service Areas*

- The NWS Mission is to provide weather, water, and climate data, forecasts, and warnings for the protection of life and property, and enhancement of the national economy.
- The NWS Vision is for a Weather Ready Nation, where society is ready, responsive and resilient to weather, water and climate dependent events.
- The NWS goal of a Weather Ready Nation (WRN) is supported by 11 Mission Service Areas (MSAs), including: (1) Aviation Weather and Volcanic Ash, (2) Fire Weather, (3)

Hydrology and Water Resources, (4) Marine Weather and Coastal Events, (5) Hurricane/Tropical Storms, (6) Routine Weather, (7) Severe Weather, (8) Space Weather, (9) Tsunami, (10) Winter Weather, and (11) Science, Services and Stewardship.

***Purpose of Priorities for Weather Research (PWR) Study Team as approved by the SAB***

- The purpose of the PWR Study Team is to evaluate and provide the information necessary to prioritize potential government investments in a requirements-based framework to advance U.S. weather research and forecasting capabilities over the next decade.
- The PWR Study is crucial for our nation because weather, water, and climate events take a significant toll on the lives and livelihoods of millions of Americans every year. Policymakers need a long-term strategy to support and fund mission-critical investments. By critically evaluating future potential needs and where to invest, the PWR Study provides guidance on research and forecasting investments that will advance capabilities of the weather enterprise to deliver improved weather information more efficiently and effectively, leading to better decisions, fewer lives lost, greater economic prosperity and a more climate & weather resilient nation.

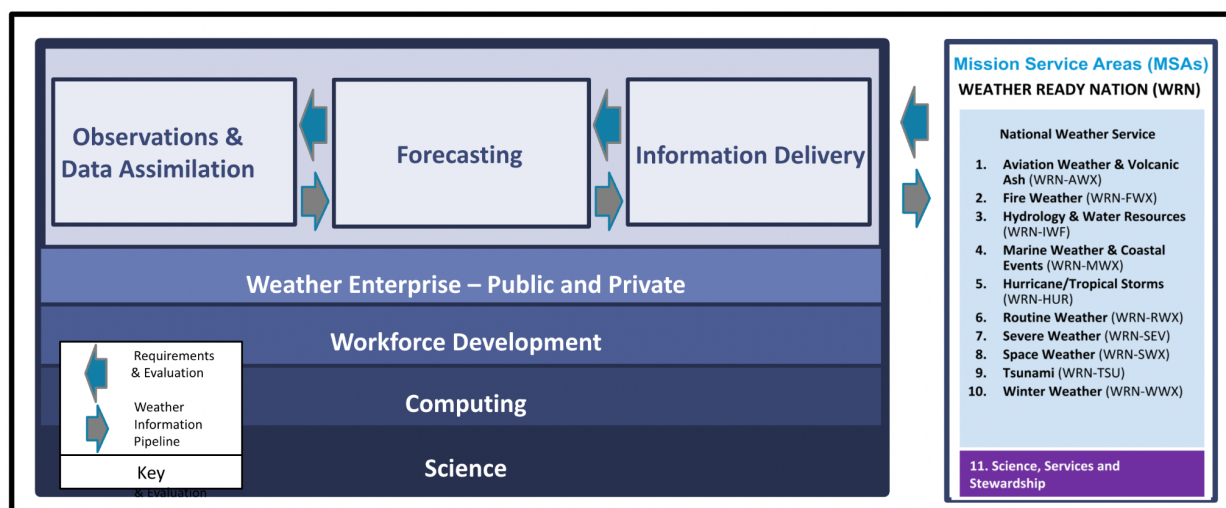
***Study Scope and Boundaries***

- Evaluate and prioritize potential weather research and forecasting investments to meet the charge given in the FY21 Omnibus Appropriations Act.
- Focus is on weather time scales defined in The Weather Research and Forecasting Innovation Act of 2017 as ranging between nowcasting (minutes) and seasonal (2 years).
- Focus is on Federal investments in NOAA, with an awareness of what other Federal agencies, private sector, and academia, can provide to advance the research and forecasting priorities.
- The Study Team will focus on identifying, evaluating and recommending priority potential investments; primarily focused on future and planned investments but may also comment on existing investments in the context of the study scope.

***Strategic Framework***

Strategic framework (Figure 1) is based on three principal pillars of the weather enterprise and their underlying foundational elements. The three pillars are: (1) Observations and Data Assimilation; (2) Forecasting; and (3) Information Delivery. The arrows in Figure 1 are critical. The left-to-right arrows indicate the driving influence that critical requirements from the Mission Service Areas and assessments of pipeline components have on the process. The resulting product flow is right to left. This feedback loop is crucial to maintain mission focus and

ensure system improvements. Science, Computing, Weather Enterprise, and Workforce Development are essential Foundational Elements for all three pillars.



### ***Prioritization Process - A Consensus Approach to Delivering a Balanced Portfolio of Recommendations***

#### **Overview**

- Given the broad scope, and limited time and resources, it was not possible to develop and apply an objective and fully reproducible prioritization system. It is noted that this report identifies a need that NOAA expand to a more objective internal process to guide better prioritization decisions for Federal weather research investments (captured in recommendations).
- The report leans heavily upon a consensus process with input from a large number of subject matter experts with broad experience from multiple sectors. The task teams had extensive prioritization discussions, reviewed a great deal of NOAA-provided material, received multiple NOAA briefings, and held mini-symposia for additional vetting of topics. While not fully objective, it is likely highly reproducible with comparable effort and a similar range of participants.
- This process was established to 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.
- Given the lack of detailed objective metrics, the priorities are not ranked individually. However, within each area the priorities will be binned into three levels of priority to indicate overall sense of importance to advancing NOAA's mission. Near the end of the

report, the section on Immediate Priorities and Common Challenges will provide some additional prioritization on process and order.

For this study and report a **high priority recommendation is defined** as one that:

- Must have high reward and benefit (gap filling, core, or innovation) with a clear connection to value, impact, or transformational potential
- Has strong linkage to NOAA through identified Requirements or aligned with Mission Service Areas (MSAs)
- Reflects a favorable balance between probability of success and reward
- Is clearly advantageous (value, impact, or transformational) to achieving NOAA's weather mission
- Has favorable context with respect to the Enterprise and the changing external World

These criteria were applied using the consensus approach across Task Team efforts to guide the overall findings and recommendations of the study.

## Section 4: External World - Overarching Trends, Environmental Equity, Risks, and Opportunities

### Overview

- NOAA's strategies and plans need to anticipate and leverage external technological, societal, and weather enterprise trends during the decade.
- This study lacked the resources to do a comprehensive survey of such trends, but we can raise awareness and provide some guidance for further NOAA thinking on the topic.

### Call out box:

"Today's Key Challenges ... faced by the National Weather Service (NWS):

- Keeping Pace with accelerating scientific and technological advancement
- Meeting Expanding and Evolving User Needs in an increasingly information-centric society
- Partnering with an Increasingly Capable Enterprise that has grown considerably"

--from [Weather Services for the Nation, Becoming Second to None](#), The National Academies Press, 2012.

### Trends

Continuing to successfully deliver on its service mission in a budget constrained environment is not a new challenge for the NWS. The National Academies 2012 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. Today the NWS still faces these plus additional challenges imposed by the external world:

- Science is increasingly cross-disciplinary, requiring expanding collaborations across Earth system science, social and behavioral sciences, and space science, for transformative progress.
- Technology advances include new observing systems, forecast models that can take advantage of rapidly advancing HPC & cloud computing capabilities, and mobile devices for interactive information dissemination
- End-users have new emerging use cases, a growing need for integrated information, and, through social science, are redefining how information is best communicated.

- 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.

### ***Environmental Equity***

- There is a disproportionate impact of climate change and high impact weather on already underserved communities. Issues of justice, equity, diversity and inclusion are at the forefront, with the need for closing gaps in data coverage and communication to less-served communities now recognized as required for growing a more inclusive Weather Ready Nation.
- Equity to ensure NOAA services are easily accessible to everyone equally AND equity in access to opportunities within NOAA

### ***Risks***

Beyond keeping pace with existing trends, new risks will arise during the next decade that will further challenge business-as-usual approaches to NOAA's mission to protect lives and property and promote economic prosperity:

- Climate change, and its impact on weather variability and extremes, produces new vulnerabilities and the need for improved weather forecasts to maintain water, food, and energy security as well as economic prosperity.
- Keeping pace with advancing science and technology requires a nimbleness that may require rethinking the integration of operational requirements and research.
- Staying nimble requires a workforce with a broader range of technical skills. Future workforces will include meteorologists working with other experts in Earth sciences, HPC, AI/ML, observing, data assimilation, modeling technologies, social sciences, etc. Strategies to increase the pipeline will be essential given the increasing demands for these skills.
- NWS is transitioning from a production-focused operational model defined by what operations is capable of providing, 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.
- Serving the US needs for global transportation, goods and services, and the U.S. 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).

## ***Opportunities***

This report was developed to identify the high priority opportunities for Federal investments that provide improved weather products and services for the U.S. The document is organized as:

- Narrative Themes that illustrate how the high priority opportunities compiled here support the Charge from Congress and the NWS service mission.
- Deep dives into the detailed findings and recommendations for each of the three Pillars (Observations & Data Assimilation, Forecasting, and Data Delivery) that support the NWS mission.
- Cross-cutting information from the three Pillars is collected and summarized in the Foundational Elements.
- A summary of Immediate Needs and Common Challenges derived from the high priority opportunities is provided.
- This is followed by Conclusions and Suggestions for Follow-Up.

## Section 5: Priorities for Federal Investment

### *Introduction*

1. There are five primary narrative themes that will highlight the broad societal benefits delivered by a focused and well-supported NOAA weather service. Each of these narrative themes will be used to highlight motivation and value of several key identified recommendations. The high-level and illustrative context - storyline - will directly relate recommendations to impacts, benefits, etc. As such, they will communicate the “Why?” motivation for the recommendations.
  - A. Mission Critical Mile
  - B. Pathway to Global Leadership in Weather Prediction
  - C. High Impact Weather
  - D. Improved Prediction of Water Cycle Extremes and their Cascading Impacts
  - E. Achieving Highly Reliable, Fully Accessible Weather Information
2. Following the narrative themes are the discussions of the three Pillars, as follows:
  - A. Observations and Data Assimilation
  - B. Forecasting
  - C. Information Delivery
3. Following the narrative themes are the discussions of the four Foundational Element Cross-cuts, as follows:
  - A. Science
  - B. Computing
  - C. Workforce Development
  - D. Weather Enterprise
  - E. Candidate mini-Crosscuts

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NOTE FOR REVIEWERS: For this extended outline deliverable, the narrative theme sections in this outline (A, B, C, D, E) present only the components of the ultimate narrative theme. I.e., we are trying to capture the elements of the storyline, but in outline components, and not the storyline. These will be transformed into prose and storylines in the next phase of writing the draft document. The list of findings, gaps, etc., will then go away.

X.1 contains the “why” content of the investment.

X.2 contains the findings, recommendations, gaps, etc., that have been aggregated from the individual task team efforts due to their broad application. They will be incorporated into the storylines of each theme.

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## 1. Narrative Themes

### A. Mission Critical Mile

#### ***Motivation, value, etc. The Why?***

Investments across NOAA, and the broader weather Enterprise, in the weather and related sciences, and the weather information delivery pipeline, have delivered remarkable results in the quality and reliability of weather forecasts and information. Unfortunately, successes cannot just be measured by the accuracy of forecasts, but must, even more importantly, be judged by the societal response to those forecasts and, ultimately, the societal value and outcome.

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. The mission critical mile has for many years been considered “the last mile” but it is now clear that it is also 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. Technical forecasts can be uninterpretable for non-experts; evacuations with short lead times may be unactionable. Understanding audiences is crucial to reaching them. 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.

Investing in mission critical mile research will enable NOAA efforts to be driven by evidence about users’ needs and barriers, that, 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, with 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.

#### ***Findings to be incorporated. Where NOAA is today, gaps, opportunities. References to pillar recommendations.***

Mission Critical Mile findings, gaps, and opportunities include:

- 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 atmospheric and other environmental data they can access (although there is room for improvement there as well). The absence of this information makes it impossible to develop critical knowledge, much less to track changes over time as new data, products, policies, and programs are implemented.

- Despite NOAA investments in Impact-Based Decision Support Services (IDSS), forecasters and others in NOAA still lack the data and tools to understand the evolving needs of diverse populations of emergency managers and other partners they are tasked to support.
- Current approaches to developing weather forecast 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.
- The complexity of weather information delivery in rapidly changing information ecosystems, together with the increasing urgency of extreme environmental event management and communication needs (*ref HIW theme*), makes 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.

## **B. Pathway to Global Leadership in Weather Prediction**

### ***Motivation, value, etc. Why?***

The skill of the computer models the U.S. uses to produce forecast guidance is not world-best, indicating that there is room for improvement in weather forecasting. While the scientific opportunities for making such improvements are well known, targeted investments are needed for the U.S. to achieve world leadership in weather prediction and better serve the American public. The pathway to world leadership in forecasting will result in advances in forecasting skill across all NOAA mission areas; improvements in all subsequent products and services; and more societally-important physical parameters being predicted. In turn, this investment will deliver significant economic benefits, more lives saved and infrastructure protected. It will also require sustained workforce development to fill evolving gaps in expertise.

The current backbone of U.S. weather prediction is the Global Forecast System (GFS), which originated as primarily an atmospheric model. However, as we look ahead, for NOAA to fully accomplish its mission of understanding, predicting and communicating changes in weather, water and climate, NOAA will be required to invest more of its ongoing development into

production systems that capture the full extent of the Earth system – atmosphere, oceans, land, coasts, ice, aerosols. As such:

- NOAA requires an Earth System Model (ESM), in which all components are coupled.
- A comprehensive and skillful ESM backbone will improve the accuracy of all UFS modeling system forecasts, from seasonal variations to high-impact weather, thus better serving the American public.
- A fully-coupled ESM will also provide opportunities for forecasts and warnings for aspects of the Earth system that are not done with today's models.

***Findings to be incorporated. Where NOAA is today, gaps, opportunities. References to pillar recommendations.***

- The skill of the GFS lags that of global models from other modeling centers, currently ranking 4<sup>th</sup>. While there are many reasons for this, one of the largest is the lack of including all relevant physical processes. It is increasingly evident that further improvement in weather modelling requires a more comprehensive treatment of the entire Earth system - atmosphere, oceans, land surface, biosphere, cryosphere, hydrologic cycle, and so on - and feedbacks between these components; i.e., an ESM framework is required.
- There are important aspects of the coupling among Earth system components that are not fully understood and research is required to advance our knowledge and ability to model the physics of intra-component interactions.
- Improvements in observations, particularly of fluxes of energy, mass and momentum between Earth system components, and advances in coupled data assimilation are essential.
- Interactions among Earth system components at mesoscales (4-20 km) are fundamentally different from large-scale interactions, and they must be accurately represented in ESMs in order to predict mesoscale features including thunderstorms, ocean eddies, polynyas, etc.
- Investments are needed to support multi-sector partnerships for the development of the next generation multi-disciplinary workforce with expertise in modeling, observing systems, data assimilation, high performance computing, big data/AI and the social sciences. (see XC-1)

## **C. High Impact Weather**

***Motivation, value, etc. The Why?***

The vision of the NWS is A Weather-Ready Nation where Society is prepared for and responds 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 over 790 deaths and \$125B in damage per year (<https://www.ncdc.noaa.gov/billions>). More accurate and timely forecasts of HIW, which are communicated to the end user effectively such that appropriate protective actions are taken, are key to mitigating risk from these events, thus saving lives and property. Perhaps include: More trustworthy forecasts, watches, warnings, messaging, etc.; better situational awareness (e.g. – fire spreading), lives and property saved, improved Air Quality Index forecasts and improved human health, economic benefits, better serving needs of underserved communities, realizing our potential capabilities, others?

***Findings to be incorporated. Where NOAA is today, gaps, opportunities. References to pillar recommendations.***

- We note that while the extreme events listed above get all the headlines, routine day-to-day weather has enormous economic impacts, often beneficial; e.g., brisk winds and sunny skies enable billions of dollars annually in energy production by wind turbines and solar arrays resp. In fact, essentially all facets of weather information - from benign temperature swings, to variability in sky cover and wind direction - can have big economic impacts within specific industries.
- While NOAA is providing valuable forecasts of HIW events today, there are many opportunities to improve observations, forecasts, and communication, of HIW events:
  - Improved physical understanding of these events, brought about by field experiments, process and predictability studies;
  - Enhanced observational capabilities, especially in the planetary boundary layer (PBL), that resolve the phenomena to be predicted;
  - Higher-resolution, convection-resolving models, nested in the UFS global model;
  - Effective and efficient DA algorithms for convection-resolving models;
  - A greater number of diverse ensembles, both for DA and forecasts, needed for extending predictability and providing probabilistic forecasts;
  - New post-processing and messaging products, aided by AI/ML tools, needed to communicate actionable guidance for all societal sectors;
  - Large increase in HPC (broadly defined) to accomplish above goals.
- Air quality (AQ), when degraded by wildfire smoke or other pollutants, is strongly related to human quality of life. Due to rising population, urbanization and climate change, wildfires are increasing and AQ is declining across the globe, thus increasing the need for and importance of AQ and fire weather forecasts, which have high societal and

economic value in preventing and mitigating property damage, disease, and mortality. Reliable predictions of fire and smoke 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. Moreover, poor AQ disproportionately affects minority and underserved communities, creating a service equity challenge for NOAA (see x.y).

## **D. Improve Prediction of Water Cycle Extremes and their Cascading Impacts**

### ***Motivation, value, etc. The Why?***

- Flood, drought, wild-fire risk and many other impacts are driven largely by extremes in precipitation, either too much or too little. This impacts public safety and the economy.
- Coastal flooding, especially when combined with river discharge and tidal cycles, is dramatic, costly, and is prime for substantial gains in forecasting
- Public safety: Reduction in risks and loss of life due to floods, which remain currently one of the greatest risks to lives and property from weather extremes
- Environmental risk equity: Communities of color become more resilient to weather and water extremes, reducing adverse economic and public safety outcomes
- Economic impacts: Adverse economic impacts can be reduced through better predictions of extreme precipitation, soil moisture, snow pack, evaporation, and runoff on time scales from minutes to weeks, months and seasons, e.g., (need Flood and Drought damage use cases)
- Climate change resiliency: Water supply reliability use case: The USACE-led Forecast-Informed Reservoir Operations (FIRO) pilot studies have demonstrated that better extreme precipitation and runoff forecasts can enable more flexible reservoir operations, which can mitigate drought/flood impacts. The more skillful the forecast, the more flexibility to hold water after a storm, or to release it ahead of a storm, expanding usefulness of \$trillions of existing dams to create greater resilience to the increasing swings between drought and flood already occurring.

### ***Findings to be incorporated. Where NOAA is today, gaps, opportunities. References to pillar recommendations.***

- Precipitation forecast skill has not improved substantially over decades and remains one of the major technical challenges in meteorology, e.g., OSTP 2020, NOAA Precipitation Prediction Grand Challenge, numerous other reports
- a leading cause of extreme precipitation forecast errors in the 1-3 day lead time in the US West coast is inherent gaps in observations of atmospheric rivers offshore

- Promising scientific and technical directions exist for which greater effort would accelerate precipitation forecast skill improvement and associated flood and drought predictions
- 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., NEXRAD coverage gaps) present barriers to success

## **E. Achieving Highly Reliable, Fully Accessible Weather Information**

### **Motivations**

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 develop platforms for inclusive and open science that deliver information to all sectors and support collaborative research and citizen science. NOAA is the primary nationally recognized 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/information access and dissemination for the weather enterprise, across and beyond NOAA.

### **Findings. Where NOAA is today, gaps, opportunities.**

Inaccessible, siloed, encumbered data and platforms hinder innovation, leading to underutilization which limits scientific discovery, new product innovation, and societal benefits. Data access and visualization software issues within the NWS (e.g., AWIPS II and satellite broadcast network (SBN)) continue to limit the effectiveness and efficiency of forecasters in and outside of the weather forecast offices (WFOs). For any kind of weather research to be useful, these immediate and ongoing operational requirements must be addressed. Climate change and extreme weather events that arise from climate change are a grand challenge affecting all people, often disproportionately affecting the economically disadvantaged. Environmental justice and leadership in this area will require an “all hands on deck” approach to draw upon scientific expertise and technology from all sectors. 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.

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 (e.g., netcdf, GeoJSON, etc.). These operational portals should be scalable, maintainable, and sustainable to meet the needs of public and private partners. Currently there are 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, etc.) and hazards (e.g., severe, tropical, fire, winter, air quality, flooding, etc.). In

particular, research and frameworks focusing on fire weather and aviation would address significant research and operational knowledge and data gaps.

**Outcomes:**

Democratizing science and data in the weather enterprise 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/crowdsourced data that are supported in a shared commons/marketplace, and a shared commons or marketplace for aviation weather data and forecasts and specifically any aircraft data/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 (e.g., Google Earth Engine); and business platforms. Modern, public, hybrid cloud platforms can be used to address multiple concerns—including robust and scalable data dissemination, information delivery to all communities, and open science and citizen science that empower communities—and support the development of a skilled workforce.

Creating open science platforms is an essential element of this theme as well as an important outcome, as open science platforms: (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, broadening access to talent, and supporting an agile and effective workforce that can be mobilized during times of crisis.

## **2. Weather Service Pillars**

### **A. Observations and Data Assimilation**

#### **Overview**

The “Observations and Data Assimilation” Pillar (Obs and DA) represents a set of recommendations to advance the underlying science, earth system monitoring and weather forecasting that supports the nation’s need for better information in many sectors, including for use of the new infrastructure being created nationally and with an eye toward environmental justice. They are envisioned as a combination with relevant “Forecasting” and “Information Delivery” recommendations and address the value cases elucidated by the “overarching themes” of the report. Based on the overall scope including lead times ranging from minutes to two years, the gaps and needs include high resolution local observation and data assimilation, e.g., for severe weather, flash flood, air quality, to observation and data assimilation of ocean and land surface/boundary layer conditions that are key to seasonal-to-two-year lead times. These recommendations support science and prediction to meet NOAA’s current mission/GPRA requirements, including those highlighted in the 2017 Weather Act, and identifies 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 technical readiness ranges from ready for operations (deploy/expand), to testing feasibility and performance (demonstrate/refine) and to emerging science and technology (invent/develop). It recognizes that some specialized science and technical capabilities are required but are not well supported by NOAA and other agencies. 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 partnership is also critical to implement innovation to operations. Getting information to users and the public are enhanced through a weather enterprise approach involving the private sector. Strategic planning and implementation of computing resources are also recommended.

#### **Focus Areas:**

- Maximize the use of under-utilized ground based in-situ, remote sensing and crowd sourced observations
- Maximize the use of underutilized satellite observations
- Regional and global reanalysis
- Coupled Earth system data assimilation
- Novel methodology and holistic infrastructure development to transformationally advance data assimilation

- National boundary layer observing system and data assimilation for weather and S2S prediction
- Observe the ocean and ocean-atmosphere boundary layers and feedbacks on weather timescales for seamless forecasting from weather to S2S
- Atmosphere River observations to improve flood and drought prediction
- Next generation diverse radar observation system and data assimilation
- Cubesat observations & data assimilation

## **B. Forecasting**

### **Overview**

Forecasting is fundamental to NOAA's mission. Despite huge assets in environmental prediction, including the largest associated research community in the world, an open data policy, and a robust private sector community, forecasting skill at the hourly to two-year time scales lags that of the international community. Foundational investments in Earth system modeling, including reanalysis and reforecasts, high impact weather, water cycle, air quality, fire weather, and coastal modeling, have the potential to enable rapid progress to world leadership in operational numerical weather prediction. The forecasting pillar includes seven priority areas for weather research that identify key areas of need and connect to the overarching themes as well as the cross-cutting areas of science, computing, workforce, and the weather enterprise.

### **Focus Areas:**

1. Foundational Earth System Modeling
2. Operational Numerical Weather Prediction Excellence
3. Routine Reanalysis and Reforecasts
4. Integrated Water Cycle Modeling
5. Coordinated Air Quality and Fire Weather
6. Actionable High-Impact Weather Forecasts
7. Comprehensive Coastal Modeling

## **C. Information Delivery**

### **Overview:**

NOAA needs a cohesive framework that coordinates and integrates the suite of challenges related to weather information delivery currently being tackled in a profusion of ways across the agency. To achieve this, our recommendations have three foci: (a) Achieving highly reliable,

easily accessible weather information to support partners and open science; (b) Promoting a virtuous cycle of collecting empirical evidence to improve weather information development and delivery, and (c) Re-orienting NOAA to achieve high scientific and institutional coordination, competence, and inclusion. These recommendations will equip NOAA with the necessary—and currently lacking—workforce, infrastructure, organizational structure, and research activities to support its strategic priorities for weather information delivery. NOAA needs to embrace hiring and training partnerships and processes to support state-of-the-art weather research on these topics and create a weather information delivery research program, in collaboration with other agencies. Addressing head-on the institutional coordination, computing, and workforce issues that currently challenge weather information delivery sciences, operations, and research-to-operations/practice-to-research transitions (see e.g., [OWA 2017](#)) will advance both the weather enterprise and meteorological justice. This framework infuses AI and cloud technologies into operational capabilities, assimilates social and behavioral data from users and assesses and anticipates key user needs (what might be called the “first mile”)—with a focus on historically underserved populations that have been made vulnerable, and creates and delivers responsive weather data and guidance products (previously called the “last mile” by many), including weather forecasts and warnings and user-driven information, in a virtuous cycle. Recognizing that NOAA has commenced some efforts along these lines that have not been fully funded and is for example short on necessary resources for computing and hiring scientific staff (e.g., relying on (nearly exhausted) hurricane supplemental funds to maintain and support important programs such as the Hurricane Forecast Improvement Program), research on weather information delivery deserves the highest priority, commensurate with the increasing criticality of weather information delivery for societal wellbeing and sustainability.

**Focus Areas:**

- Highly available and disaster-proof data access
- NOAA-wide weather enterprise data integration and dissemination
- Open science development and support
- Multi- and interdisciplinary research on equitable and effective use, usability, and usefulness of hazardous weather information
- Probabilistic and deterministic hazard information delivery capabilities
- Multi-dimensional metrics, data repositories, and new data collection methods and standards for “baseline” and event-specific social and behavioral data
- Weather-knowledge ecosystem and workforce development strategies
- Interdisciplinary/convergent weather information development and delivery research program

### 3. Foundational Element Cross-cut Priorities

Overview: There are four Foundational Cross-cut Elements that provide the essential underpinning for the three pillars just discussed. Namely:

- Science
- Computing
- Workforce Development
- Weather Enterprise

**A. Science** - includes improved understanding of: earth system science that influences the models and the observations; human, social and behavioral sciences that influence how products are developed and delivered; and the research for all potential transitions and feedback loops (research to operations/applications to research, R2X2R) that ensures new science is efficiently made available for sustained operational activities.

- Behavioral and social sciences
- Earth system science
- Space weather
- Emerging interdisciplinary sciences and weather applications (e.g., AI/ML)
- Balance of RL science across Federal agencies

**B. Computing** - is critically necessary for all three Pillars and includes consideration of high performance computing (HPC), application of cloud computing, cyber infrastructure for data storage and transfer, and security.

- National need for orders of magnitude more computer power
- NOAA R&D computing program
- Today's computing environment is highly dynamic, which presents challenges
- Balance of research and production computing resources

**C. Workforce Development** - including training & education, diversity, and early career engagement. It emphasizes the critical importance of people. Investment in training and education, both initially and ongoing, is essential to maintain a competent, diversified workforce, particularly given the rapid pace of change in today's technology. Looking ahead to the next generation of weather scientists and forecasters, and engaging them early as students, is imperative.

- The overall workforce pipeline
- Internal Federal / NOAA workforce management
- Federal investments into future workforce

**D. Weather Enterprise** - government, industry, academic. This cross-cut emphasizes that no single organization can do everything and succeed on its own. Multiple government agencies, the private sector, and academia all have roles to play. Collaboration and Public Private Partnerships (PPP) are essential for overall success. Collaboration and partnerships do not just happen on their own and deserve significant investment of time and resources to ensure success.

- Unified Forecast System - Community-based, coupled, comprehensive Earth modeling system - local to global, sub-hourly to seasonal
- Earth Prediction Innovation Center - EPIC - accelerate community enhancements to NWP
- The Enterprise is critical to Information Delivery
- The Enterprise is critical to Increasingly complex observing systems, many within private industry, or operated through government, industry, academic partnerships.

**E. Candidate mini cross cuts**

1. NOAA prioritization system
2. Improved metrics to measure success, set goals, and focus resources
3. Funding

## **Section 6: Immediate Priorities and Common Challenges**

Topics to be called out and discussed:

- Structured cross line-office systems and an integrated approach to budget decisions
- The climate crisis, WRN, and Weather Enterprise roles
- Support of historically underserved and socially vulnerable communities with relevant weather, water and climate information
- Partnerships, collaborations, and the leveraging of existing and expanding mechanisms
- Balance of Readiness Level (RL) efforts and their distribution and gaps
- Workforce training
- Gaps in critical priority areas
- HPC strategy and requirements

## Section 7: Concluding Remarks and Suggestions for Follow-Up

### Collected Remarks include:

- More objective methods to help set priorities and to track progress are needed and should be developed.
- The layered group consensus process used here could be repeated in five years.
- EISWG annual Report to Congress is an existing mechanism within the SAB structure that provides an opportunity for follow-up.

## **Appendices**

- I. Study Approach
  - A. Study Team Organization & Membership (based on Figure 2 from Scoping Document)
  - B. Parallel Information Gathering Pipeline (based on Figure 3 from Scoping Document)
  - C. Participants & Conflict of Interest Statement
  - D. Meeting Log
- II. NOAA information repository (links to reports and documents provided by NOAA)
- III. Definitions