REPORT TO CONGRESS

WEATHER RESEARCH AND DEVELOPMENT PLANNING REPORT

Developed pursuant to: Title I, Section 105 of the Weather Research and Forecasting Innovation Act, 2017, 15 U.S.C. § 8515

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TITLE I, SECTION 105 OF THE WEATHER RESEARCH AND FORECASTING INNOVATION ACT, 2017 (15 U.S.C. § 8515) INCLUDED THE FOLLOWING LANGUAGE

Not later than 1 year after April 18, 2017, and not less frequently than once each year thereafter, the Under Secretary, acting through the Assistant Administrator for Oceanic and Atmospheric Research and in coordination with the Director of the National Weather Service and the Assistant Administrator for Satellite and Information Services, shall issue a research and development and research to operations plan to restore and maintain United States leadership in numerical weather prediction and forecasting that—

(1) describes the forecasting skill and technology goals, objectives, and progress of the National Oceanic and Atmospheric Administration in carrying out the program conducted under section 8512 of this title;

(2) identifies and prioritizes specific research and development activities, and performance metrics, weighted to meet the operational weather mission of the National Weather Service to achieve a weather-ready Nation;

(3) describes how the program will collaborate with stakeholders, including the United States weather industry and academic partners; and

(4) identifies, through consultation with the National Science Foundation, the United States weather industry, and academic partners, research necessary to enhance the integration of social science knowledge into weather forecast and warning processes, including to improve the communication of threat information necessary to enable improved severe weather planning and decision making on the part of individuals and communities.

THIS REPORT RESPONDS TO THE CONGRESSIONAL REQUIREMENT.

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I. EXECUTIVE SUMMARY

The Weather Research and Forecasting Innovation Act of 2017 (15 U.S.C. § 8501 note, hereafter, the "Weather Act") and the National Integrated Drought Information System (NIDIS) Reauthorization Act of 2018 (15 U.S.C. § 8501 note) directs 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. This annual planning report (hereafter, "the plan") describes the short- and long-term plan of the National Oceanic and Atmospheric Administration (NOAA), part of the Department of Commerce, to achieve the Weather Act's goal of restoring and maintaining United States' leadership in numerical weather prediction and forecasting, through collaborative efforts between NOAA's Office of Oceanic and Atmospheric Research (OAR), National Weather Service (NWS), and National Environmental Satellite, Data, and Information Service (NESDIS). The plan includes a research and development (R&D), as well as a research to operations (R2O), approach in accomplishing the aforementioned goal.

To regain and maintain leadership in numerical weather prediction and forecasting, NOAA must transition from a deterministic model-of-the-day approach to a probabilistic ensemble approach, where the forecast and its uncertainty are addressed and integrated into operational forecasts. The following plan details the agency's 5-year and 10-year technical configuration goals for developing the world's best numerical weather prediction and forecasting modeling system. It also includes the various components essential for success, including: continued support of fundamental research activities, prioritizing stakeholder and community engagement, and standing up transformational R&D activities such as the Earth Prediction Innovation Center (EPIC), the Joint Technology Transfer Initiative (JTTI), and the Hurricane Forecast Improvement Program (HFIP). The plan is explicitly designed to accelerate community-developed scientific and technological advancements into the operational applications for numerical weather prediction. It is expected that embracing these measures, in addition to enhancing integration of social and behavioral sciences to meet the public's growing weather forecast needs, will help the United States achieve its goal of regaining leadership in numerical weather prediction and forecasting.

Numerical modeling guidance has been the cornerstone of most weather forecasting for decades and covers scales from minutes (for severe weather) up to 2 years (for seasonal outlooks). The foundation for restoring and maintaining leadership in weather prediction and forecasting is the Next Generation Global Prediction System (NGGPS), which aims to transform and simplify the NWS National Centers for Environmental Prediction (NCEP) Production Suite – NOAA's multi-layered modeling suite (hereafter, the "production suite") – through the use of a community-based Unified Forecast System (UFS). Operational models used by the NWS for operational weather forecasting are run on a fixed schedule by NCEP's Central Operations, and includes various environmental applications, such as ice, ocean and wave models.

Evolving from its previous set of models which were initially designed to address individual problems, NOAA's primary vision for the revised production suite is to create the world's best integrated modeling system, unifying timescales from an analysis of current conditions (now) to seasonal prediction (2-year scale). The system will also integrate environmental subcomponents of the atmosphere, oceans, land, ice, hydrology, and aerosols, in a scientifically sound, community-based, social science informed, and economically justifiable way to support NOAA's operational mission most efficiently.[1] Moving to a simplified production suite requires a user-driven product-focused design where requirements drive technical development, using models that are adopted to provide the required products. The end goal is to move from a quilt of models to a unified modeling approach, focusing limited resources on a smaller number of models that encompass the nation's weather prediction needs. Additionally, this unified modeling system has contributed to the National Earth System Prediction Capability (ESPC), now the Interagency Council for Advancing Meteorological Services, which incorporates the activities and responsibilities of the National ESPC.[2]

Community involvement in modeling is fostered in part through the NOAA Testbeds and Proving Grounds, offering an unparalleled forum for academics, model developers, core partners, and front-line forecasters to interact with experimental model data and evaluate data and tools in a realistic in-person and virtual operational environments. EPIC also serves a critical role by fostering community engagement and enabling the transition of modeling innovations from the community into operational production systems. While the agency continues its investments in foundational research, NOAA also recognizes the need for integrated activities that combine both fundamental research and stakeholder community engagement. This is demonstrated through NOAA's investments in transitional research activities that link research, development, demonstration, and deployment using significant, new research and development products to meet NOAA's mission needs.

Continuing engagement with stakeholders and the modeling community will also be critical to achieving NGGPS's goals. To meet this vision and achieve community engagement, NOAA will leverage community-wide expertise while providing ease of access to data and information, and will continue to interact with stakeholders through numerous mechanisms, including web-based surveys, assessment reports, community meetings, direct engagement (such as with emergency managers) before, during, and after weather events, as well as through formal Social, Behavioral and Economic Science (SBES) projects. SBES will also help NOAA assess societal information, preparedness, reception, and risk perception, to understand how to blend forecast advancements into usable output to empower societal response. NOAA will use internal programs, such as the Weather-Ready Nation Ambassadors program, Regional Collaboration Teams, the National Sea Grant College Program, and the Climate Adaptation Partnerships Program (formerly known as the Regional Integrated Sciences and Assessments Program), to regularly solicit input from stakeholders and to provide updates on NOAA's activities.

[1] As described in the "2017-2018 Roadmap for the Production Suite at NCEP" (2020)

[2] Interagency Council for Advancing Meteorological Services (www.icams-portal.gov/faq.htm)

II. INTRODUCTION

This planning report is in response to title I, section 105 (codified at 15 U.S.C. § 8515) of the Weather Research and Forecasting Innovation Act of 2017 (15 U.S.C. § 8501note; hereafter referred to as the "Weather Act"), signed into law on April 18, 2017.

Not later than 1 year after April 18, 2017, and not less frequently than once each year thereafter, the Under Secretary, acting through the Assistant Administrator for Oceanic and Atmospheric Research and in coordination with the Director of the National Weather Service and the Assistant Administrator for Satellite and Information Services, shall issue a research and development and research to operations plan to restore and maintain United States leadership in numerical weather prediction and forecasting that—

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III. BACKGROUND

Numerical modeling guidance has been the cornerstone of most weather forecasting for decades and covers scales from minutes (for severe weather) up to 2 years (for seasonal outlooks). Operational models used by the NWS for operational weather forecasting are run on a fixed schedule by the NOAA NCEP Central Operations. This set of models is referred to as the *Production Suite at NCEP* (hereafter referred to as "production suite") – and includes many other environmental applications, such as ice, ocean and wave models. Several NOAA organizations in addition to NCEP contribute to the production suite; in particular, the NWS Meteorological Development Laboratory, the NWS Office of Water Prediction, all OAR laboratories and program offices, NESDIS, and the NOAA National Ocean Service Center for Operational – Oceanographic Products and Services.

External reviews of NCEP by the University Corporation for Atmospheric Research (UCAR) Community Advisory Committee for NCEP (UCACN)[3] have long observed that the current

[3] UCAR Community Advisory Committee for NCEP Final Reports, 2009-2015 (https://cpaess.ucar.edu/ucacn/final-reports)

operational modeling suite is too complicated and needs to be simplified. In response, the NCEP director requested the UCACN to stand up the UCACN Model Advisory Committee (UMAC), charging the committee to review the entire production suite, which was completed in December 2015. Key findings of the UMAC included the need for simplifying the production suite and the development of a strategic plan to accomplish the task, as well as the need to leverage the entire weather enterprise in order for NOAA's weather services to become "second-to-none" and maintain numerical modeling leadership (National Academy of Sciences, 2012[4]).

In 2016, NOAA embarked on a project to restore and maintain the Nation's leadership in numerical weather prediction and forecasting, entitled the Next Generation Global Prediction System (NGGPS). To ensure that the system would continue to improve through research and modeling contributions by the larger weather enterprise of scientists in government, academia, and the private sector, as described by the Weather Act, the project utilizes a community modeling framework - a two-way exchange of information, where a community of users contributes feedback using agreed-upon metrics and procedures. This approach has been used throughout the project and has guided the creation of various NOAA plans, including strategic vision and roadmap documents, as well as annual implementation plans.

IV. GOALS AND OBJECTIVES

NOAA's vision for the production suite is to create the world's best integrated modeling system that unifies timescales from an analysis of current conditions (now) to seasonal prediction (2-year scale). The system will also integrate environmental subcomponents of the atmosphere, oceans, land, ice, hydrology, and aerosols, in a scientifically sound, community-based, social science informed, and economically justifiable way to support NOAA's operational mission most efficiently.[5] To meet this vision and achieve community engagement, NOAA will use community-wide expertise while providing ease of access to data and information. The ultimate goal for the unified modeling system is a national system where all core partners have true ownership. This unified modeling system, forming part of NOAA's modeling suite, has contributed to the ESPC, which extends from near-real-time to decadal scales. These efforts will continue to leverage existing partnerships coordinated by the National ESPC, which has been deactivated as a separate entity, and the newly formed Interagency Council for Advancing Meteorological Services, which now incorporates the activities and responsibilities of the National ESPC.[6]

The current production suite has evolved over several decades as a set of models designed to address individual problems, rather than providing products to satisfy technical requirements. This resulted in a quilt of models, creating multiple model approaches with overlapping functions and products. Moving to a simplified production suite requires a user-driven product-focused design where requirements drive technical development, using models that are adopted to provide the required products. As a result, having a product-oriented operational modeling

[4] National Research Council (2012), Weather Services for the Nation: Becoming Second to None. Washington, DC: The National Academies Press. https://doi.org/10.17226/13429

[5] As described in the "2017-2018 Roadmap for the Production Suite at NCEP" (2020)

[6] Interagency Council for Advancing Meteorological Services (www.icams-portal.gov/faq.htm)

suite requires a governance structure that strongly enforces a product-based approach and avoids one-off model implementations. The end goal is to move from this quilt of models to a unified modeling approach, focusing limited resources on a smaller number of models that encompass the nation's weather prediction needs.

Figure 1 represents a simplified depiction of the proposed unified modeling system. The green box represents the UFS, comprising the Unified Coupled Model and Unified Data Assimilation. The blue boxes, or elements, represent various timescales for the subsequent forecast systems, ranging from nowcasts through decadal timescales and beyond. The "Year +" element identifies modeling beyond the one-year range. The "Year" element addresses seasonal forecasting. The "Month" element addresses services for week 3-4 (sub-seasonal) predictions. The "Week" element addresses traditional medium-range weather forecasting. The "Day" element addresses the rapid refresh short-range forecasts, with a focus on convection and severe weather. The "Hour" element addresses envisioned Warn-on-Forecast (WoF) approaches, with a forecast of only a few hours, produced (on demand) several times per hour. Finally, the "Now" range covers traditional global analyses, as well as envisioned rapidly updating full-atmosphere analyses.[7] The WoF, Traditional Analyses (Trad), and Rapidly Updated Analyses (RUA) represent forecasts on the regional scale.

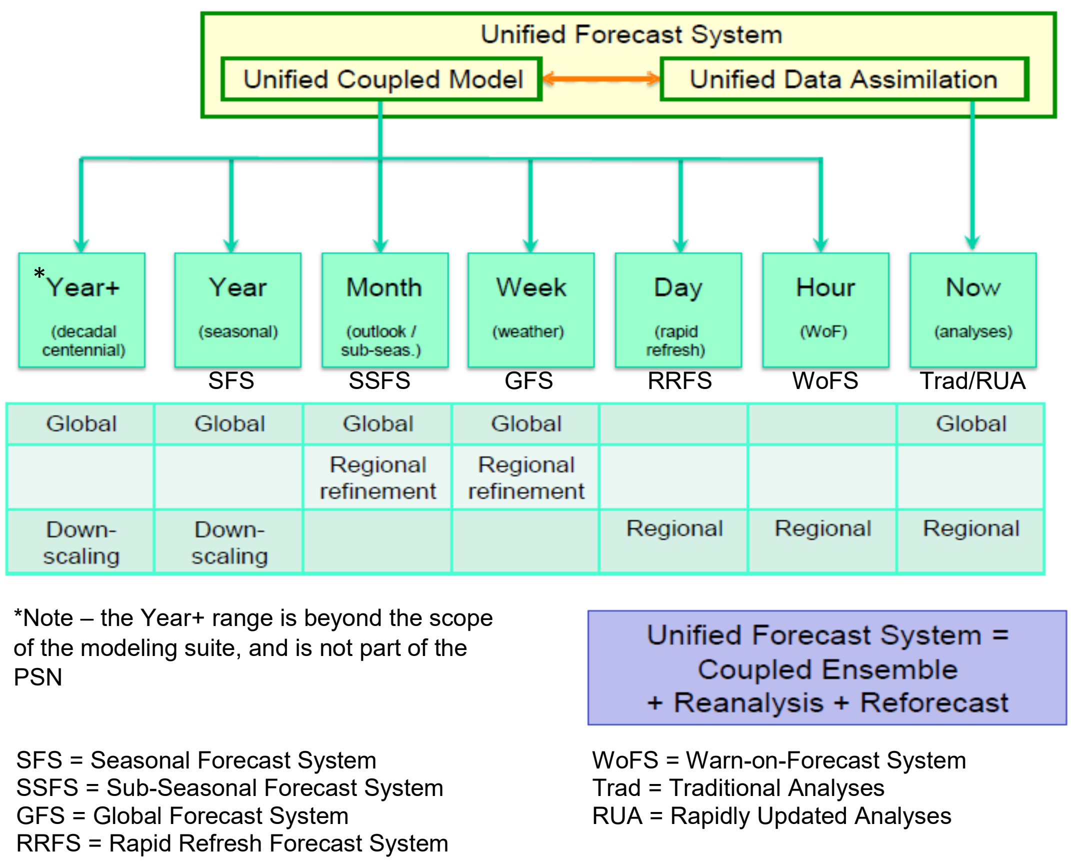

Figure 1: High-level Design of a Unified Modeling System

[7] As described in "A Strategic Vision for the NOAA's Physical Environmental Modeling Enterprise" (2020)

The Seasonal Forecast System, Subseasonal Forecast System and Global Forecast System (SFS, SSFS and GFS, respectively) are inherently global in scale. These applications will be based on a single Unified Global Coupled Model, and a Unified Data Assimilation approach, which are expected to evolve within the community-based UFS across all time scales. A global approach may include variable resolutions with a focus on mission areas for NOAA (e.g., United States, Guam, Puerto Rico, and American Samoa), or specific target areas during extreme events such as fire weather and hurricanes. The convection allowing Rapid Refresh Forecast System (RRFS) and WoFS are inherently regional and will eventually cover all NWS areas of responsibility. NOAA is pursuing a Unified Data Assimilation approach through support and engagement with the common data assimilation software under development with the NOAA-NASA-DoD Joint Center for Satellite Data Assimilation (JCSDA).

Table 1: Five-Year Production Suite at NCEP Forecast Goals[8]

Forecast Systems	Run Frequency	Range	Resolution	Number of Ensemble Members[9]
Seasonal Forecast System (SFS)	7 days	9-15 months	50 km (global)	28
Sub-Seasonal Forecast System (SSFS)	24 hours	35-45 days	35 km (global)	31
Global Forecast System (GFS)	6 hours	7-10 days	13 km (global)	26
Rapid Refresh Forecast System (RRFS)	1 hour 6-12 hours 6-12 hours	18 hours 30 hours 60 hours	3 km (regional)	26
Warn-on-Forecast System (WoFS)	5-15 minutes	2-4 hours	1 km (regional)	26
Analyses **Traditional** **Rapidly Updated Analysis (RUA)**	6-24 hours 15 minutes	--- ---	Variable (global) TBD (regional)	--- ---

8 2017-2018 Roadmap for the Production Suite at NCEP (https://cpaess.ucar.edu/sites/default/files/meetings/2017/documents/Tolman_Toepfer_Production_Suite.pdf)

9 The process of running two or more related but different analytical models, and then synthesizing the results into a single score, to improve the accuracy of predictive analytics. Each separate model is considered a member of the entire ensemble.

*Note – Red text indicates that the capability does not exist in the current NOAA modeling suite

The future skill of the modeling system will ultimately be assessed by how well the model output helps NOAA meet its Government Performance and Results Act (GPRA) weather goals. To meet GPRA goals and to address the Nation's need for increasingly accurate, reliable, and high-resolution environmental information, NOAA has adopted 5-year and 10-year technical configuration goals for developing the world's best numerical weather prediction and forecasting system. From the global perspective, development in moving to this design has already begun with the NGGPS project. Table 1 represents a minimum configuration needed to consolidate and unify the operational modeling suite, to be achieved in 5 years.

The SFS, SSFS, GFS, RRFS, WoFS and analyses form the core of the unified production suite. The suite will also include NOAA's hurricane models, space weather models, the National Water Model, wave prediction systems, coastal and estuarine models (including storm surge models), air quality models, tsunami models, and models driven by data from the National Digital Forecast Database, some of which have already been successfully integrated.

V. STATUS OF U.S. WEATHER MODELS AND FORECASTING SKILL

The Weather Research and Forecasting Innovation Act of 2017 (15 U.S.C. § 8501 note) and the National Integrated Drought Information System (NIDIS) Reauthorization Act of 2018 (15 U.S.C. § 8501 note) direct 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. NOAA is in the process of addressing the new requirements by establishing a community modeling paradigm where the NWS draws from intellectual capital throughout the Weather Enterprise – including public, private, and academic entities – to develop the best possible operational models.

NOAA has achieved significant progress in improving the predictive skill of its operational numerical weather prediction models. The anomaly correlation coefficient (ACC) is one of the most widely used forecast verification statistics and is defined as the correlation between anomalies of forecasts and those of verifying observations or analyses. One metric to measure useful forecast days over the hemispheres is when the 500-hPa geopotential height ACC exceeds 0.6, which corresponds to the threshold up to where there is useful skill for the largest scale weather systems.

Figure 2 illustrates a comparison of the ACC between the GFS (shown in black) and the European Center Model (labeled ECM, shown in red) from 1984-2022. The slope of the lines increases towards an ACC of 1.0, indicating overall improvements of the models to corresponding observations. In addition, the gap between the lines has narrowed during this time, demonstrating accelerated improvements of the GFS when compared to the ECM.

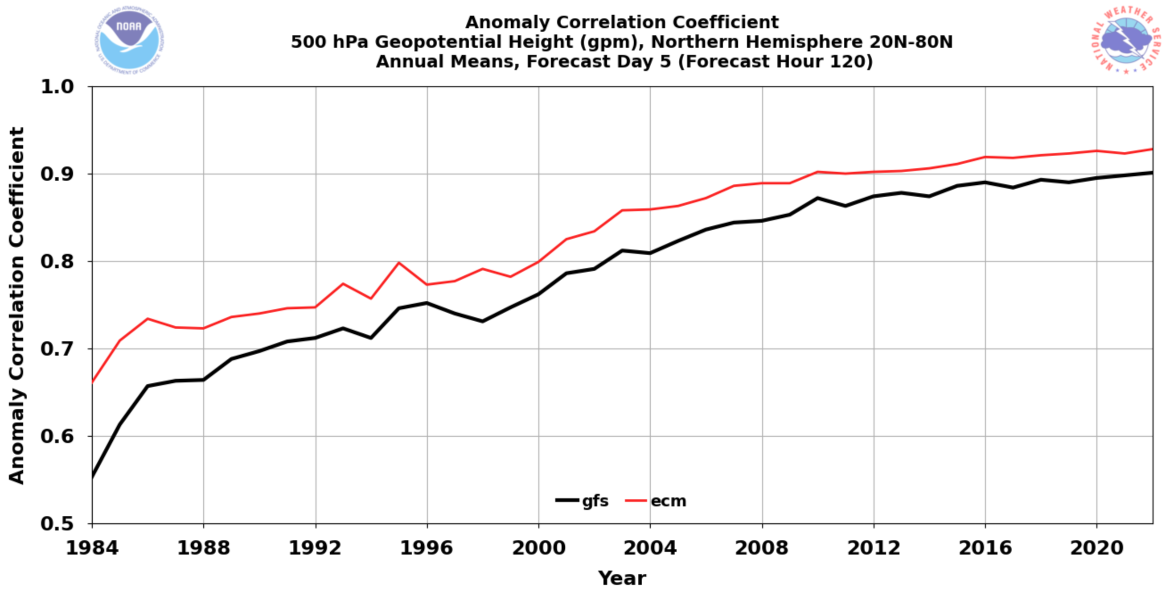

Figure 2: Forecast Accuracy – Northern Hemisphere 500-hPa Height Anomaly Correlation

NOAA's GFS shows a steady increase of useful forecast days by about 1 day per decade in the past 30 years (1989-2022) over the Northern Hemisphere (Figure 3),[10] which is comparable to other leading international numerical weather prediction centers. For example, using an ACC of 0.6, the GFS useful skill forecast reached 8.40 days in 2022, while the European Centre for Medium-Range Weather Forecasts useful skill forecast reached 8.85 days.

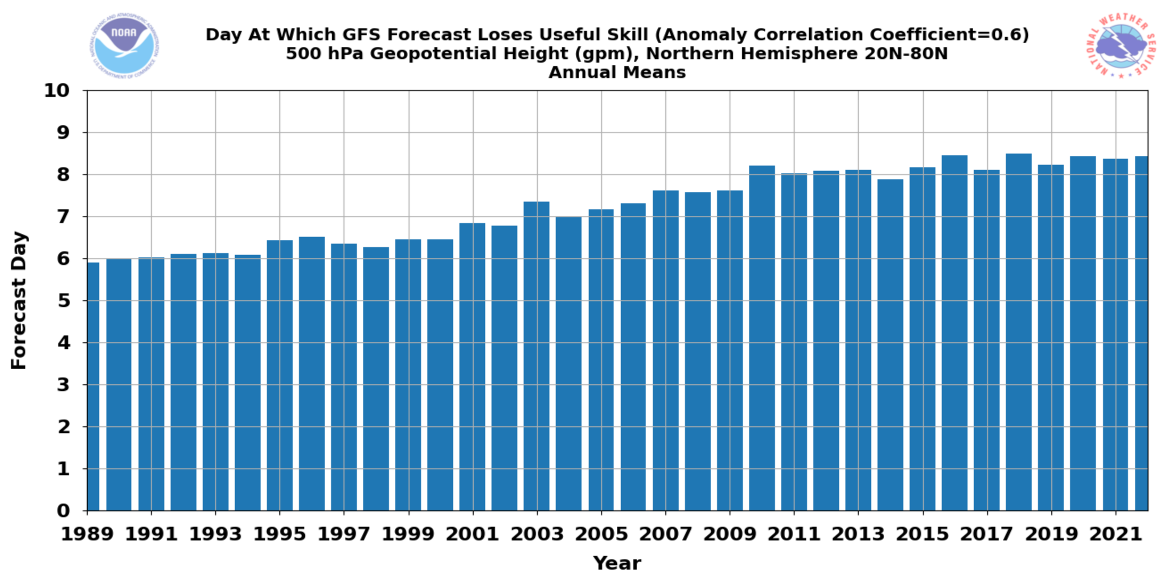

Figure 3: Forecast Accuracy: Useful Skill Forecast at 500-hPa Geopotential Height, 1989-2022

[10] Data provided by the Verification, Post-Processing, and Product Generation Branch at the NOAA Environmental Modeling Center.

The recently upgraded GFS forms the basis of the first public release of the UFS-based medium range weather and subseasonal to seasonal forecast applications so that subsequent upgrades can incorporate innovations from the broad weather research community. The latest version of GFS also fully couples to the community-based WAVEWATCH III application for predicting ocean waves. This is only one of several UFS applications that will cover the extent of weather phenomena needed for improving overall predictions. For info on stance, higher resolution numerical predictions are covered by the release of the UFS short-range (up to 2 days) weather application in March 2021, with a focus on severe weather prediction to support the next operational regional prediction system.

NOAA implemented its first global-scale coupled operational weather forecasting system in 2020. The Global Ensemble Forecast System upgrade (GEFSv12) integrated the Finite-Volume Cubed Sphere (FV3) atmospheric model to wave and aerosol components. For the first time, GEFSv12 extended NOAA's useful prediction of precipitation by one full day and significantly improved the skill of its probabilistic wave forecasts. The upgraded ensemble system will serve as the basis for GEFSv13, the first UFS-based, fully coupled – land-atmosphere-ocean-ice – operational community-based earth system model at NOAA that will advance sub-seasonal to seasonal forecasts.

Moving forward, NOAA is investing in operational prediction suite improvements through implementation of community-based modeling by adopting the UFS as its source system. UFS applications span the broad range of NOAA's prediction portfolio, including severe weather and other weather extremes, e.g., hurricanes, air quality, seasonal forecasts, marine winds, space weather, aviation, and global prediction, some of which are unique capabilities within the U.S. forecast enterprise. This contrasts with the European Centre for Medium-Range Weather Forecasts, which focuses on medium-range global forecasts. NOAA has also established the Earth Prediction Innovation Center (EPIC), facilitating the transition of modeling innovation sourced from both community and NOAA collaborators into operational production systems.

VI. FUNDAMENTAL RESEARCH ACTIVITIES

The layout of a unified production suite as presented in the previous section is essential for the efficient operation and development of the modeling suite. It will not, however, accomplish the goal of creating the best operational suite of numerical weather prediction and forecasting models in the world. A target moonshot layout of the production suite necessary to achieve and maintain leadership in numerical weather modeling within the next 10 years is presented in Table 2. The aggressive nature of this layout will be adjusted based on evidence-based decision protocols and resource availability.

Attaining the goals described in Table 2 is not without its challenges. For example, significant computational resources and infrastructure for both the operations and R&D will be required to meet the goal of becoming the best in numerical weather prediction and forecasting and ensuring the ensuing outputs can be delivered to forecasters and the weather and water enterprise efficiently on various timescales. Similarly, if investment in next-generation high performance computational resources – both on-premise and in-cloud – facility support, skilled software engineering workforce and new technologies, and engaging partners in both the public and private sectors is not done in parallel for both operations and R&D with a greater capacity of supercomputing across NOAA, that will cause delays in achieving these goals because of the tight coordination needed to transition research into operations.

Table 2: Ten-Year Moonshot Production Suite at NCEP Forecast Execution Goals[11]

Forecast Systems	Run Frequency	Range	Resolution	Number of Ensemble Members
***S3FS**	7 days	12 months	15 km (global)	200
	24 hours	45 days		100
GFS	1-6 hours	7-10 days	5 km (global)	50
RRFS	1 hour 3 hours 6 hours	24 hours 48 hours 72 hours	1.5 km (regional)	50
WoFS	5 minutes	2 hours	0.5 km (regional)	50
Analyses **Trad.** **RUA**	 6-24 hours 5 minutes	 --- ---	 Variable (global) TBD (regional)	 --- ---

*S3FS = Single-coupled Seasonal and Sub-Seasonal Forecast System

Significant improvements between the 5-year plan and the 10-year layout include:

- The development of a single-coupled forecast system, the Single-coupled Seasonal and Sub-Seasonal Forecast System (S3FS), to represent seasonal and sub-seasonal forecasts;
- Increase in run frequency for the RRFS and WoFS;
- Increased resolution at all timescales for all forecast systems to improve forecast precision;
- Reduction in time range for forecasts; and
- Increased number of ensemble members, improving forecast uncertainty information.

It is also critical that we sustain investment in the observations and assimilation of observations into the forecast systems that are needed to improve the forecast skill. Nevertheless, setting such ambitious goals is essential for the U.S. to field the best numerical weather prediction and forecasting modeling enterprise in the world for two reasons. First, it sets a direction for R&D that needs to start today, to reach the 10-year goals; and second, it allows the agency to address

[11] 2017-2018 Roadmap for the Production Suite at NCEP (https://ufscommunity.org/wp-content/uploads/2020/06/20200423_2017-2018_Roadmap_for_PSN.pdf)

resource needs proactively, as it starts providing a cost-benefit analysis for necessary investments in computing and research.

It is important to note that NOAA has received funding for operational supercomputing to support the building and development of the Weather & Climate Operational Supercomputing System, and recent supplemental funding from various legislation including the Infrastructure Investment and Jobs Act of 2021, the Disaster Relief Supplemental Appropriations Act of 2022, and Inflation Reduction Act of 2022, has added to NOAA's research supercomputing capabilities. Furthermore, to achieve the goal of having the world's preeminent numerical weather prediction and forecasting system, continuing research is required to constantly improve NOAA's environmental modeling enterprise feeding into the operational modeling suite. Given the current state of technology and modeling capabilities, many barriers exist to transitioning research into the operational modeling system.[12] The agency's modeling enterprise will require research in areas that are applicable to many time scales. This research, including the areas described in 15 U.S.C. § 8512 of the Weather Act, will fully support the community modeling framework, and will be conducted by NOAA and its partners in academia, the Federal Government, and the private sector, working together to ensure resources are applied to critical research needs to meet the outlined goals.

Key areas of research being pursued by NOAA and its partners to support the development of the new operational modeling suite are:

- **Predictability studies** – particularly important for seasonal and subseasonal timescales as well as for convective storms to determine the predictability time limit of storm-scale models that are expected to provide accurate forecasts beyond 1 hour;
- **Model physics** – research will include best representation of clouds, chemistry, rain formation, vegetation, ocean mixing and biology, to improve predictions at all timescales;
- **Full coupling of the Earth system** – including interactions across boundaries associated with the atmosphere, ocean, ice, ground, and space, critical to determining the degree to which coupling of the Earth system elements is required to improve predictions at all timescales;
- **Data assimilation** – to improve model predictions using data assimilation of observations from *in situ* and remote sensing instruments from minutes to months;
- **Ensemble design** – to improve representation of the full range of prediction possibilities, needed for all prediction timescales, from storm-scale to seasonal;
- **Probabilities** – both as model inputs and outputs, probabilistic information will allow for frequently-updated guidance, which will help communicate forecasts and their risks more effectively;
- **Post-processing** – essential to maximize the quality and accuracy of model guidance provided to the forecast at all spatial and temporal scales;
- **Validation and verification** – to incorporate an increasing set of process-based metrics, to be extended from being weather-centric to cover the whole environmental modeling effort (including interactions between modeling components);

[12] As described in NOAA Administrative Order 216-115B: Research and Development in NOAA (www.noaa.gov/organization/administration/nao-216-115b-research-and-development-in-noaa)

- **Configuration management –** to ensure a flexible, modular system amenable to frequent community updates to modeling systems;
- **Artificial intelligence and machine learning** – more efficiently represent parameterized processes, accelerate model integrations, and data assimilation; and
- **Social science** – focus on understanding human behavior to identify how to maximize the interaction of forecasters with modelers through optimizing the translation of model guidance and model data into forecasted hazard information (including conveying probabilities), and subsequent products, services, and messaging to empower effective response from the public and decision-makers.

VII. STAKEHOLDER AND COMMUNITY ENGAGEMENT

NOAA embarked on a community-based, social science informed approach to model development with the NGGPS in the mid-2010s (also in section VII D). The new production suite will use a community modeling approach that involves NOAA, other Federal partners, the private sector, and the research and academic community at large. The community approach will include testing and evaluation and model component coupling, and may be formalized through organizations such as the Developmental Testbed Center (DTC), a partnership between NOAA, the U.S. Air Force, and the National Science Foundation's (NSF) National Center for Atmospheric Research (NCAR). To that end, NOAA entered into a Memorandum of Agreement with NCAR on January 30, 2019, to assist weather and climate modeling scientists in achieving these goals through more strategic collaboration, shared resources, and information. Only with appropriate contributions from the entire modeling community will the development of the best national modeling system be possible.

Seeking greater community involvement in the weather model development process, NOAA has expanded the use of open-development tools to enable community modeling, with EPIC at the center of this effort. One tool utilized by EPIC and NOAA is GitHub, a web-based hosting service used for collaborative code development that allows open-source sharing of data and code. Groups or individuals can download NOAA's master codes, add innovations, submit their modifications, and create collaborative environments across institutions, companies, or other organizations. Using tools like GitHub, weather model development is no longer limited to NOAA. Instead, it now includes scientists and researchers from agencies, academia, and the private sector, maximizing the use of expertise across the weather enterprise.

Community involvement in modeling is also fostered through the NOAA Testbeds and Proving Grounds. Testbeds and Proving Grounds offer an unparalleled forum for academics, model developers, core partners, and front-line forecasters to interact with experimental model data and evaluate data and tools in a realistic in-person and virtual operational environment. The unique mix of perspectives help sharpen the NOAA modeling direction and inform innovative solutions for new (or updated) products, services, and messaging.

Community partnerships enable NOAA to develop operational prototypes and transition several community models to operations, unified around a common atmospheric dynamic core, the FV3 model. Examples include the Community Radiative Transfer Model, the wave modeling package WAVEWATCH III, the Community Ice CodE, and the Common Community Physics Package. NOAA's new paradigm phases out the practice of single institutions developing code, leveraging resources, and maximizing the transition of new ideas to operations by welcoming contributions from experts throughout the modeling community.

Continuing engagement with stakeholders and the modeling community will be critical to achieving NGGPS's goals. NOAA will continue to interact with stakeholders through numerous mechanisms, including web-based surveys, assessment reports, community meetings, direct engagement (such as emergency managers) before, during, and after weather events, as well as through formal SBES projects. NOAA will use internal programs and offices, such as the Weather-Ready Nation Ambassadors program, Regional Collaboration Teams, the National Sea Grant College Program, and the Climate Adaptation Partnerships/Regional Integrated Sciences and Assessments Program, to regularly solicit input from stakeholders and to provide updates on NOAA's activities. These collaborations will leverage the expertise of our Federal partners, a key example being USDA's Climate Hubs Program, to gain insight into the needs of communities with uniquely focused requirements for products and services.

Best practices have shown that different levels of community partners should be established with specific roles and responsibilities, such as:

- ***Trusted superusers*** who can have more advanced access than occasional research users. So that they can conduct beta-testing, test early prototypes, etc.;
- ***Core development partners*** who regularly make substantial contributions to the development of the system have different roles than casual users that run the model but do not contribute to its development; and
- ***Users and stakeholders*** who, while not contributing to the code in general, contribute requirements and needs, and drive the direction of development, resource allocations and prioritization (within the NOAA mission). These users are also critical, as they tend to provide a level of in-depth evaluation of model performance that cannot be provided by super-users and core-developers, only.

With this community approach to modeling, all core partners have a voice in making strategic decisions, not just the operational center.

To effectively coordinate the activities of the community partners, as well as to manage the collaborative projects of those partners, a robust community governance structure will be established based on several core principles and values:

- **Commitment by core development partners:** The community-based unified forecast system (UFS) is designed to be a national system where all core partners are truly invested and empowered. This implies that each core development partner will need to consider their role on the national team as a fundamental and enduring priority for their respective organization, and that each core development partner will have a voice in making strategic decisions, not just the operational center(s);
- **Informed practices:** The governance structure will leverage successful practices from tried-and-true structures in prior and existing community modeling systems;
- **Community Values:**

- Promotes an environment for individuals to succeed by recognizing talent in diverse communities, providing opportunities for career advancement, and providing incentives to make decisions in context of community and system requirements (collaborative rather than individual decision-making);
- Evidence-based decision making that is requirements-driven and considers the balance of cost, requirements, scientific credibility, and user experience;
- Supports a scientific organization, committed to process improvement (verification, validation, documentation, reduce redundancy of systems, optimization of human and computational resources); and
- Trust and transparency.

The proposed governance structure is intended to be led by an executive steering committee and a set of working groups that will represent the essential science, technical, and design aspects of the unified production suite. The working groups will span the community of expertise needed to support the unified system, with specific areas of focus and functionality:

- **Science working groups,** for example land modeling, where focus might be on a component model, with scientific development a high priority;
- **Systems working groups,** for example, systems architecture, verification and validation, ensembles, communications, and end-users – where the focus is on the system as a whole, the community as a whole, and meeting an optimization of technical and scientific requirements, as well as cost;
- **Applications working groups,** for example, Medium-range Global, Seasonal, Space Weather, where the components are brought together as a configuration to address the requirements of a particular application.

A. The Environmental Information Services Working Group (EISWG)

To reaffirm its interest and commitment to community engagement at various levels, the U.S. Congress mandated continuation of the NOAA Science Advisory Board (SAB) EISWG. The Weather Act assigns EISWG the responsibility of providing advice for prioritizing weather research initiatives at NOAA, to produce real improvements in weather forecasting. The EISWG is further instructed to provide advice on emerging technologies and techniques within private industry and/or the research community that could be incorporated into forecasting at the NWS to improve forecasting skill. These efforts are encouraged to focus on improving communications and partnerships between NOAA and the private and academic sectors, as well as weather forecasters, other Federal agencies, state, local and tribal governments, and emergency management personnel and the public.

Composed of leading experts and innovators in various fields, the EISWG submits an annual report to the SAB, which is then transmitted to Congress, on NOAA's progress in adopting their recommendations. This mandate requires and fosters direct engagement with subject matter experts from across America's weather enterprise. In response, the EISWG is committed to delivering valuable insights to NOAA and Congress. The EISWG works closely with NOAA Line Offices to assess NOAA's progress toward meeting the Weather Act objectives. An important part of this close collaboration is a prioritization process that both ensures attention to the most critical topics and also recognizes the limits on what the EISWG can accomplish. The EISWG also continues to explore ways to optimize both the review process and the value of its feedback including: leveraging additional information gathering opportunities; engaging NOAA experts more frequently and informally; and continuously redesigning and improving its own internal report-writing and review processes. As a result, the EISWG is becoming increasingly effective at addressing topics within the Weather Act identified and systematically prioritized through this collaborative process.

Since the implementation of the Weather Act in 2017, the EISWG has provided reviews and recommendations to NOAA on a variety of topics, including but not limited to:

- Use of Observing Systems Simulation Experiments within NOAA;
- Hazards Simplification and Communication;
- Hurricane Forecast Improvement Program (HFIP);
- Tornado Warning Improvement and Extension Program Plan;
- Feedback on the EPIC Strategic Plan; and
- NOAA SAB Report on Priorities for Weather Research.

NOAA will continue to provide updates to the EISWG and Congress, through a variety of reporting mechanisms. A partial list of recent weather-related reports and plans can be found in Appendix A.

B. NOAA SAB Report on Priorities for Weather Research (PWR)

In December 2020, Congress charged the NOAA SAB to develop a report providing information (including benefits) necessary to prioritize Federal investments in weather research and forecasting over the next decade.

> ***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."*
>
> *~ FY 2021 Omnibus Consolidated Appropriations Act, Book 1, page 232*

In response to this direction, the NOAA SAB launched the Priorities for Weather Research (PWR) study. Through a broad consultative process led by the EISWG, the study engaged over 150 subject matter experts from within NOAA, and across the weather enterprise. Submitted to Congress in December 2021, the report strongly recommended accelerated and increased investments in priority areas that build upon – and are balanced across – the entire weather information value chain. Considered in its entirety, the recommended investments would be transformational, enabling NOAA to meet accelerating weather, water and climate challenges, better protect life and property, and promote greater economic prosperity and environmental justice for all.[13]

The overarching consensus of the study and report recognized an urgent need to immediately expand U.S. investments in weather research and forecasting, as well as a dramatic increase over the next decade. Highlighting these findings, 33 recommendations were identified by the PWR Team, spanning four core areas: 1) Research and Development; 2) Infrastructure; 3) Action and Impacts; and 4) NOAA Prioritization and Investment. Several recommendations focusing on improvement and acceleration of weather research and numerical weather prediction were incorporated into the report, including but not limited to:

- Accelerate Earth system model development and seamless prediction - to improve forecasts of all components of the Earth system – atmosphere, oceans, cryosphere, and land – on all time and space scales;
- 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;
- Establish a regular, sustained Earth system reforecasting activity – to enable a more effective cadence and accelerated process for operational model improvements; and
- Prioritize immediate investments in fundamental research on data assimilation to deliver sustained improvements in forecasting skill, and to train the next generation of experts in this area to fill an existing critical workforce gap.

NOAA provided its response to the SAB report in December 2022, including current activities being undertaken by the agency to address the critical needs as described, as well as planned activities. In large part, NOAA concurred with the report's findings, with additional resources required to meet many of the PWR Team's recommendations.[14]

VIII. TRANSITIONAL RESEARCH ACTIVITIES

NOAA's ability to meet its mission through the delivery of continually improved products and services relies on the conversion of the best available research and development endeavors into operational and application products, commercialization, and other uses. While the agency continues its investments in foundational research, NOAA also recognizes the need for integrated activities that combine both fundamental research (as described in section IV) and stakeholder community engagement (referenced in Section V). As such, NOAA invests in transitional research activities that link research, development, demonstration, and deployment using significant, new research and development products to meet NOAA's mission needs. Examples of programs focusing on these activities include the following:

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[13] NOAA Science Advisory Board, 2021: A Report on Priorities for Weather Research. NOAA Science Advisory Board Report, 119 pp. (https://sab.noaa.gov/wp-content/uploads/2021/12/PWR-Report_Final_12-9-21.pdf)
[14] The SAB PWR report and NOAA's response can be found on the NOAA SAB website (https://sab.noaa.gov/)

A. Joint Technology Transfer Initiative (JTTI)

OAR has carried out the JTTI initiative in coordination with NWS since 2016, and in cooperation with America's weather industry and academic partners. JTTI's primary mission is to ensure continuous development and transition of the latest scientific and technological advances for NWS operations; and to establish a process to sunset outdated and expensive operational methods and tools to enable cost-effective transfer of new methods and tools into operations. OAR's Weather Program Office[15] (WPO) manages this initiative, using a competitive selection process to identify promising transition projects. With the completion of competitions in FY 2020, JTTI has supported 98 projects, with 68 projects increasing by at least one Readiness Level. In FY 2021, 20 projects were selected for funding. Since its inception, 15 projects have transitioned to operations by NWS, and it is expected that several of the remaining JTTI projects will transition into NWS operations over the next 3-to-8 years, many of which are focused on community-based UFS-related activities.

B. Earth Prediction Innovation Center (EPIC)

Section 105 of the Weather Act (15 U.S.C. § 8515) explicitly 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 Reauthorization Act of 2018 (15 U.S.C. § 8501 note) instructs NOAA to establish EPIC to accelerate community-developed scientific and technological enhancements into the operational applications for numerical weather prediction. Specifically, section 4 amends section 102(b) of the Weather Act (15 U.S.C. § 8512(b)) to add the following responsibilities:

> "Advancing weather modeling skill, reclaiming and maintaining international leadership in the area of numerical weather prediction, and improving the transition of research into operations by—
>
> A. Leveraging the weather enterprise to provide expertise on removing barriers to improving numerical weather prediction;
> B. Enabling scientists and engineers to effectively collaborate in areas important for improving operational global numerical weather prediction skill, including model development, data assimilation techniques, systems architecture integration, and computational efficiencies;
> C. Strengthening the National Oceanic and Atmospheric Administration's ability to undertake research projects in pursuit of substantial advancements in weather forecast skill;
> D. Utilizing and leverage [sic] existing resources across the National Oceanic and Atmospheric Administration enterprise; and
> E. Creating a community global weather research modeling system that—
>   i. Is accessible by the public;
>   ii. Meets basic end-user requirements for running on public computers and networks located outside of secure National Oceanic and Atmospheric Administration information and technology systems; and

[15] Formerly the Office of Weather and Air Quality (OWAQ)

iii. Utilizes innovative strategies and methods whenever appropriate and cost-effective, including cloud-based computing capabilities, for hosting and management of part or all of the system described in this subsection."

The transition of innovative research into operations and operational gaps into research priorities (R2O2R) for numerical modeling has been studied for decades, with continued emphasis on how to improve transition processes. Several interagency agreements between NOAA, the National Aeronautics and Space Administration (NASA), the U.S. Forest Service, the U.S. Air Force, the U.S. Navy, and NSF support efforts to specifically address satellite data assimilation (via the JCSDA, established in 2001) and mesoscale modeling (via the DTC, established in 1999). These activities have produced examples where transitioning R2O2R was improved through collaboration, coordination, and co-development of algorithms and tools commonly used by its member institutions. EPIC will accelerate the transition of innovative research and development into operations, through its focus on community-developed enhancements and cooperation. EPIC's focus is to enable the UFS, a community-based, coupled, comprehensive Earth modeling system, to become the most accurate and reliable operational numerical forecast model in the world. Software engineering, software infrastructure, user support services, cloud-based high-performance computing, scientific innovation, management and planning, and external engagement are all within EPIC's purview. EPIC will continue to engage partners from across the weather enterprise through its web portal, and community workshops and events, to advance weather prediction for the benefit of society. This, in turn, will simplify the NWS operational production suite, while adopting a unified modeling strategy co-developed with other Federal agencies, industry, and academia.

C. United States Weather Research Program (USWRP)

The USWRP, managed by WPO, supports the transition of research in five critical areas to produce advances in observational, computing, and modeling capabilities to foster substantial improvement in weather forecasting and prediction of high-impact weather events: 1) heavy precipitation and associated flooding; 2) tropical storms; 3) air quality; 4) severe weather; and 5) the social science necessary to improve the communication of weather information to decision-makers. USWRP provides funds for NOAA scientists, researchers and academic partners to collaborate in transitioning this research into useful applications that help forecasters provide more accurate, reliable, and usable weather forecasts and warnings. These funds also support societal impact studies in weather and a set of related program projects to provide outreach and coordination among NOAA, other government agencies, academia, and industry. A significant portion of USWRP includes NOAA's testbeds and proving grounds.[16]

Most of the USWRP-supported transition activities have been associated with three NOAA testbeds: the Hydrometeorology Testbed, located at the NWS Weather Prediction Center in College Park, Maryland; the Hurricane and Ocean Testbed (formerly the Joint Hurricane Testbed), located at the NWS National Hurricane Center (NHC) in Miami, Florida; and the Hazardous Weather Testbed located at the Storm Prediction Center in Norman, Oklahoma. Testbeds facilitate the orderly transition of research capabilities to operational implementation through development testing and operational readiness/suitability evaluation. The USWRP

[16] www.testbeds.noaa.gov/

supports projects across universities, NOAA Cooperative Institutes, and private companies that test and demonstrate new cutting-edge science and technology the NWS can use operationally to improve NOAA's weather, air quality, and hydrologic forecasting services for the public.

Recently funded testbed projects include high-resolution regional convection allowing models and ensemble forecast techniques, which produce probabilistic forecasts (i.e., forecasts that consider the likelihood, or probability, that an event will occur) in addition to standard deterministic (e.g., binary, yes/no) forecasts. If proven successful, these projects will demonstrate new applications that NWS forecasters may use if implemented operationally. Once in use operationally, these applications are expected to improve the quality and timeliness of forecasts for high-impact weather, such as tornadoes, severe thunderstorms, flooding, fire weather and smoke, and hurricanes.

D. Next Generation Global Prediction System (NGGPS) / Unified Forecast System (UFS)

NWS is designing, developing, and implementing an ensemble-based global prediction system to address growing service demands for probabilistic information, and to increase the accuracy of weather forecasts out to 30 days. The work is expanding critical weather forecasting R2O through accelerated development and implementation of current global weather prediction models, improved data assimilation techniques, software architecture, and system engineering. Contributions from a wide sector of the numerical weather prediction community including NOAA and other agency laboratories and universities, are incorporated into an operational system to deliver an NGGPS that meets the evolving national prediction requirements. Over the past three years, the UFS has been established according to a Strategic Implementation Plan (FY 2019-2021) which was developed by NOAA together with the broader numerical weather prediction community. The UFS is a national unified Earth system modeling system for operations and research, to the mutual benefit of both.

Teams composed of subject matter experts across NOAA line offices/laboratories, Navy, NASA, U.S. Forest Service, UCAR, and universities continue to provide updated input on the direction of the UFS, which builds off the original NGGPS program plans. Forecast application teams have formed around particular forecast systems including medium-range weather, short-range regional weather, hurricanes, subseasonal-to-seasonal, atmospheric composition, and space weather. Among its significant accomplishments, the UFS has established the FV3 Dynamical Core for all UFS applications. It has released, with support from EPIC, both the operational medium range weather application and the developmental short-range weather application to the community. Several community infrastructure codes have been developed and adopted in UFS, including the Joint Effort for Data assimilation Integration, the Common Community Physics Package, METplus for model validation, and various model coupling systems. In the coming three years, a fully coupled (atmosphere, ocean, land, ice, waves, and atmospheric composition) global ensemble forecast system will be released and provided for community development and collaboration.

E. Collaborative Science, Technology, and Applied Research (CSTAR) Program

The CSTAR Program, within the NOAA/NWS Office of Science and Technology Integration, represents an effort to create a cost-effective transition of applied research directly to NWS forecast operations and services through collaborative research between operational forecasters and academic institutions which have expertise in the environmental, social and behavioral sciences. These activities engage researchers and students in applied research of interest to the operational meteorological community and improve the accuracy of forecasts and warnings of environmental hazards by applying scientific knowledge and information to operational products and services. There are currently 14 ongoing CSTAR projects. Nine of these projects began in 2019-2020, and were selected from proposals addressing near-term NWS science priorities to improve forecasts and warnings. The remaining five CSTAR projects began in 2022, and focus on research and development topics relating to the improvement of operational services to historically underserved and socially vulnerable communities.

F. Hurricane Forecast Improvement Program (HFIP)

The HFIP was established within NOAA in 2007, to improve hurricane track and intensity forecasts. The HFIP was highly successful in the first 10 years, reducing errors in track and intensity forecasts. In 2017, section 104 of the Weather Act required the next phase of HFIP to focus on three main areas: 1) improving prediction of rapid intensification and track of tropical cyclones (TC); 2) improving the forecast and communication of surges from TCs; and 3) incorporating risk communication research to create more effective watch and warning products.

HFIP provides a unified organizational infrastructure and resources for NOAA and the broader community to coordinate the research needed to significantly improve guidance for hurricane track, intensity, and storm surge forecasts, and to accelerate the transition of promising technologies and techniques from the research community into operations. Through three rounds of grants competitions, HFIP supported 10 projects that were either intended to be transitioned to the NHC operations, or integrated into the UFS-based Hurricane Analysis and Forecast System.

G. NOAA's Artificial Intelligence (AI) Strategy

NOAA is incorporating artificial intelligence (AI) and machine learning (ML) into modeling, as set out in the NOAA Artificial Intelligence Strategy.[17] Objective 3.2 states the plan to transition to operations, commercialization, and academia AI-based environmental data and application with NOAA-approved metrics. NOAA is applying AI/ML to develop models that are more computationally efficient, and to optimize data processing both types of data assimilated into the models, and of post-processing model output.

H. Data Assimilation (DA)

Data assimilation (DA) advances are key to improving forecast systems. NOAA partners with other agencies to support and implement DA software development in JCSDA. This shared software facilitates efficient improvements in DA methods, as well as easier incorporation of new data. Skilled expertise in DA is particularly needed. Therefore, NOAA is prioritizing the

[17] NOAA Artificial Intelligence Strategy: Analytics for Next-Generation Earth Science (2020)

training of DA experts through funding opportunities and hiring at NOAA institutions, centers, laboratories, and cooperative institutes.

IX. SOCIAL, BEHAVIORAL AND ECONOMIC SCIENCE (SBES) INTEGRATION

Social scientists play a critical role in connecting the improvements of NOAA's weather modeling system to the goal of meeting the public's growing weather forecast needs. Social science will inform how best to optimize the usability of forecaster operational tools that incorporate new forecast technologies, evaluating and understanding the cognitive decision demands on the human forecaster, as well as on the external users of this information. SBES will also help NOAA assess societal information, preparedness, reception, and risk perception, to understand how to blend forecast advancements into usable output to empower societal response. Social science[18] plays an end-to-end role in ensuring the full potential of NOAA's investment in numerical weather prediction.

The importance of integrating social sciences into the forecast and warning process was identified in a 2017 National Academy of Sciences (NAS) Report,[19] sponsored by NOAA and the Federal Highway Administration. Written by an interdisciplinary, multi-sector committee representing the weather enterprise, the report engaged several Federal agencies, including NOAA and NSF, the private sector, academia, and stakeholders, and recommended a framework for generating and applying social science research within the context of meteorology, weather forecasting, and weather preparedness and response. It also identified opportunities to accelerate relevant findings and better engage researchers and practitioners from multiple social science fields with the weather enterprise, including multiple users of weather information. Some relevant highlights include:

- **An assessment of the current state of social sciences within the weather enterprise,** including research, previous agendas, research to applications challenges and barriers, and inconsistent funding challenges;
- **A framework to sustainably support and effectively use social science research in the weather enterprise,** through possible organizational arrangements to integrate social science research, as well as possible mechanisms to fund research through Federal support (including NOAA and NSF), as well as public-private partnerships;
- **Research needs for improving the Nation's weather readiness and advancing fundamental social science knowledge,** outlining critical knowledge gaps in three areas:
  - *Weather Enterprise System-Focused Research* – how individuals (including forecasters) access, interpret and use weather information and observations across the weather enterprise, as well as how society values weather enterprise data and services;

[18] The NOAA Science Advisory Board report defines social science as "the process of describing, explaining and predicting human behavior and institutional structure in interaction with their environments." It includes diverse disciplines, such as communication, economics, psychology, geography, political science, etc.

[19] Integrating Social and Behavioral Sciences within the Weather Enterprise, November 2017. (www.nap.edu/catalog/24865/integrating-social-and-behavioral-sciences-within-the-weather-enterprise)

- *Risk assessments and response, and factors influencing these processes* – encompasses how individuals perceive and respond to risk, and understanding the unique needs of various populations, as well as key professional communities; and
- *Message design, delivery, interpretation, and use* – consists of learning how to most effectively tailor forecasts, warnings, and recommendations to the needs of different audiences.

To enhance the integration of SBES knowledge, the report identifies three key recommendations:

(1) The adoption of social science expertise into leadership teams, and establishing relevant policies and goals to effect necessary organizational changes;
(2) Federal agencies, coupled with America's Weather Industry and social science scholars, work to identify specific investments and activities that collectively advance research at the social science-weather interface, as well as commitments to more sustainable institutional capacity for research and operations at the social science-weather interface among other Federal agencies that play critical roles in weather related research operations; and
(3) Increased support of research efforts in the areas stated above (weather enterprise system-focused research; risk assessments and response; message design), including impacts of false alarms, forecast uncertainty, and consistent messaging across the weather enterprise.

The NAS report represents an important step in articulating how to incorporate social sciences into the forecast process, as well as important research necessary to improve communication of important weather information. These recommendations are being used to inform current and future engagements between NOAA and NSF, with a focus on identifying collaborative activities to address these recommendations.

X. SUMMARY

Numerical weather forecasting is moving from a deterministic model-of-the-day approach to a probabilistic ensemble approach, where the forecast and its uncertainty are addressed and integrated into operational forecasts. The tenets behind probabilistic forecasting, including social science communications, probabilistic hazard information and human-centered design, are important for the future of forecasting in the NWS. As a result, the development of a unified operational modeling suite is necessary to improve forecast accuracy and determine uncertainty. Efforts to transition related research and applications into forecast operations are supported by multiple NOAA programs with increasing emphasis on connecting forecasts to user decisions through integration of social and behavioral science. When completed, the UFS will form the backbone of NOAA's future operational prediction capability meeting the public's evolving needs for more accurate, more specific, longer lead-time weather forecasts. With availability of resources, this will move the Nation to lead the weather enterprise in numerical weather modeling and forecasting for years to come.

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XI. LIST OF ACRONYMS

ACC	Anomaly Correlation Coefficient
AI	Artificial Intelligence
CSTAR	Collaborative Science, Technology, and Applied Research Program
DA	Data Assimilation
DTC	Developmental Testbed Center
ECM	European Center Model
EISWG	Environmental Information Services Working Group
EPIC	Earth Prediction Innovation Center
ESPC	Earth System Prediction Capability
FV3	Finite-Volume Cubed Sphere
GEFSv12	Global Ensemble Forecast System upgrade
GFS	Global Forecast System
GPRA	Government Performance and Results Act
HFIP	Hurricane Forecast Improvement Program
JCSDA	Joint Center for Satellite Data Assimilation
JTTI	Joint Technology Transfer Initiative
ML	Machine Learning
NAS	National Academy of Sciences
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
NGGPS	Next Generation Global Prediction System
NHC	National Hurricane Center
NIDIS	National Integrated Drought Information System
NOAA	National Oceanic and Atmospheric Administration
NSF	National Science Foundation
NWS	National Weather Service

OAR	Oceanic and Atmospheric Research
PWR	Priorities for Weather Research
R2O[2R]	Research to Operations [to Research]
R&D	Research and Development
RRFS	Rapid Refresh Forecast System
RUA	Rapidly Updated Analyses
S3FS	Single-coupled Seasonal and Sub-Seasonal Forecast System
SAB	Science Advisory Board
SBES	Social, Behavioral and Economic Science
SFS	Seasonal Forecast System
SSFS	Sub-Seasonal Forecast System
Trad	Traditional Analyses
TC	Tropical Cyclone
UCACN	UCAR Community Advisory Committee for NCEP
UCAR	University Corporation for Atmospheric Research
UFS	Unified Forecast System
UMAC	UCACN Model Advisory Committee
U.S.	United States
USWRP	United States Weather Research Program
WoF	Warn-on-Forecast
WoFS	Warn-on-Forecast System
WPO	Weather Program Office

Appendix A: List of NOAA Weather Act and Weather-Related Reports and Plans April 2018 through December 2022

Report Title	Description
Sec. 102 - Report to Congress: Weather Research and Forecasting Innovation: Annual Report of Current and Planned Activities within the Office of Oceanic and Atmospheric Research	This annual report describes and highlights current and planned activities within the Office of Oceanic and Atmospheric Research (OAR), in support of its vision to improve all forecasts; detect changes in Earth's oceans and atmosphere; explore its marine environment; and drive science innovation.
Sec. 103 - Report to Congress: Tornado Warning Improvement and Extension Program Plan	The Tornado Warning Improvement and Extension Program (TWIEP) Plan describes the short-term and long-term efforts of NOAA to achieve the Weather Act's goal of tornado prediction beyond 1 hour. The plan details the observations and science necessary to develop and support this goal, promotes the use of social science to develop more effective ways to communicate information to the public and emergency management community, and empower society to make protective action decisions and maximize the effectiveness of forecast improvements.
Sec. 104 - Report to Congress: Hurricane Forecast Improvement Program	The Hurricane Forecast Improvement Program (HFIP) began in 2009 and has significantly improved forecast performance for the last 10 years, while meeting its 5-year goal to reduce track and intensity errors by 20 percent. The next generation of HFIP will continue its mission to reduce impacts of hurricanes through the implementation of key strategies designed to improve forecasts and warnings, while continuing to address existing science and R2O challenges to achieve the objectives outlined for the next generation of HFIP.
Sec. 109 - Report to Congress: United States Weather Research Program Annual Project Report	The USWRP funds projects that test and demonstrate new cutting-edge science and technology, which NWS can use operationally to improve NOAA's weather and hydrologic forecasting services for the public. Most USWRP-supported transition activities have been associated with three NOAA testbeds: the Hydrometeorology Testbed, the Joint Hurricane Testbed, and the Hazardous Weather Testbed. USWRP also funds projects at universities, NOAA Cooperative Institutes, and private companies that seek to improve NWS weather and air quality forecasting services.
Sec. 201 - Report to Congress: Subseasonal and Seasonal	This report outlines the current use of NOAA's subseasonal to seasonal (S2S) products and services, and how NOAA plans to improve the usability and transference of data, information, and

Forecasting Innovation: Plans for the Twenty-First Century	forecasts. Developed with input from Federal, regional, state, tribal, and local government agencies, research institutions, and the private sector, it will serve as a guidepost for planning and execution, as well as to inform the public and NOAA's stakeholders on its efforts on subseasonal and seasonal forecasting.
Sec. 301(a) - Report to Congress: Short-Term Management of Environmental Observations - Microsatellite Constellations	The COSMIC-1 mission launched six microsatellites in 2006, for a new, inexpensive atmospheric radio occultation (RO) sounding technique. Two of the original six microsatellites continue to transmit data useful in NWS numerical weather prediction models. NOAA and its partners initiated the COSMIC-2 program to continue to RO mission, as well as launch 12 satellites (6 polar, 6 equatorial); however, deployment has been decreased to the equatorial orbiting satellites only.
Sec. 301(b) - Report to Congress: Radio Occultation Data Gap Mitigation Plan	The COSMIC-1 mission was launched in 2006 as a proof-of-concept for a new, inexpensive radio occultation (RO) atmospheric sounding technique as a partnership between Taiwan and the U.S., and led by the National Science Foundation with participation of the National Aeronautics and Space Administration (NASA), U.S. Air Force, and NOAA. Since early 2007, high fidelity RO atmospheric profile data from COSMIC-1 have led to important, measurable improvements in weather forecasts, and space weather monitoring and research.
Sec. 302 - Report to Congress: Commercial Weather Data Pilot Program	This report describes the results of the Commercial Weather Data Pilot (CWDP) Round No.1 project conducted by NOAA in 2016 and 2017. The report describes the project initiation and execution, summarizes the technical results and lessons learned by NOAA, and presents an assessment of the current readiness of the commercial radio occultation (RO) industry to provide viable operational weather data to meet NOAA's needs.
Sec. 403 - Report to Congress: Office of Oceanic and Atmospheric Research and National Weather Service Exchange Program	The recommended exchange program at NOAA between the Office of Oceanic and Atmospheric Research (OAR) and the National Weather Service (NWS) has developed through scientific collaborations driven by research projects, operational needs, and co-location of facilities. To meet the guidance of the Weather Act, OAR and NWS will promote exchanges of up to 1 year between OAR research scientists and NWS forecasters and scientists, through existing OAR programs, with additional emphasis on opportunities between Line Office staff.

Sec. 406 - Report to Congress: Improving NOAA Communication of Hazardous Weather and Water Events	Congress has directed NOAA to assess its system for issuing watches and warnings regarding hazardous weather and water events, as well as submit a report on the findings of that assessment. This report summarizes activities that NOAA has undertaken to assess the current hazard messaging system. The National Weather Service (NWS) has led improvements to its Watch, Warning, and Advisory (WWA) system, designed to better convey expected hazard certainty and severity in various areas including (but are not limited to) winter weather, tropical storms, fire weather and smoke, severe thunderstorms, tornadoes, flooding, drought, and excessive heat/cold.
Sec. 410 - Report to Congress: The NOAA's Report on Contract Positions at the National Weather Service	This report provides an analysis of full-time equivalent (FTE) employees to an analysis of contractor support at NWS. The report also includes NOAA's response to the Department of Commerce (DOC) Office of the Inspector General's (OIG) investigation into the use of contractors by the NWS.
Sec. 414 - Report to Congress: Gaps in NEXRAD Radar Coverage	The study examines the impact of radar coverage on warnings for tornadoes and flash floods, noting that radar also provides necessary observations to support other weather warnings (e.g., hail/severe thunderstorms, winter weather, hurricanes, etc.,) that are not addressed by the study and this report. Tornadoes and flash floods are rare events in general, and only a small fraction of those events cause fatalities. Data from the NEXRAD network are critical for tornado and flash flood warnings, and forecasters also use information from satellites, surface observations, storm-spotters, and high-resolution forecast models (among other sources) to aid in the forecast and warning process.
Sec. 509 - Report to Congress: The NOAA's Report on Tsunami Warning & Education Act	NOAA continues to operate a comprehensive, end-to-end tsunami forecast, warning, and mitigation capability, and continues its ongoing efforts to engage Federal, state, tribal, and local partners through administering the National Tsunami Hazard Mitigation Program, as directed by the Tsunami Warning and Education Act (TWEA). NOAA has also been effective in obtaining the necessary supercomputing resources to run its tsunami prediction models, targeting increases to speed and accuracy of near-field tsunami detection, measurement, and forecasting.
NOAA Science Advisory Board (SAB) Report on Priorities for Weather Research (PWR)	In December 2020, Congress charged the NOAA SAB to develop a report providing information (including benefits) necessary to prioritize Federal investments in weather research and forecasting over the next decade. Submitted to Congress in December 2021, the report strongly recommended accelerated and increased investments in priority areas that build upon - and are balanced across - the entire weather information value chain.

NOAA Response to the Science Advisory Board (SAB) Report on Priorities for Weather Research (PWR)	As a requirement of the congressional request, NOAA provided its response to the SAB-PWR report in December 2022, including current activities being undertaken by the agency to address the critical needs as described, as well as planned activities. In large part, NOAA concurred with the report's findings, with additional resources required to meet several of the identified recommendations.
OAR Strategic Plan, 2020-2026	OAR has updated its strategic plan, to effectively deliver NOAA's future, including improving all forecasts, driving innovative science, and remaining competitive in the environmental R&D market. The new strategy helps to guide OAR's future research and resource decisions, to foster a pioneering and integrated research enterprise dedicated to advancing understanding of the oceans and atmosphere.
EPIC Five-Year Strategic Plan	The Earth Prediction Innovation Center's (EPIC) Five-year Strategic Plan provides a framework describing NOAA's approach to facilitate innovation and accelerated research to operations (R2O) improvements in operational modeling. The plan describes EPIC's vision to address the entire UFS community by fostering partnerships and community engagement, with the goal of improving the Nation's numerical weather prediction and forecasting.
Precipitation Prediction Grand Challenge Strategic Plan	The Precipitation Prediction Grand Challenge (PPGC) Strategic Plan outlines an integrated set of objectives and actions that, when implemented, will advance understanding of predictability, improve process level understanding, and improve prediction systems to address the atmospheric and oceanic variability associated with predictability limits and prediction skill.
OAR Cloud Computing Strategy	The vision of the OAR Cloud Computing Strategy is to implement cloud-enabled, mission-centric capabilities, whenever possible. This strategy will leverage key benefits of the cloud such as dynamically scalable computing resources, consistent easy-to-use tools and techniques which speed up innovation, improve security, and provide cost benefits due to economy of scale. The strategy envisions a secure, scalable, cost effective, and data-source agnostic path to forward the goals and objectives outlined in the OAR Strategic Plan.
Triennial Report on Computing Resources Prioritization	Maintaining and growing High Performance Computing (HPC) capability is one of NOAA's highest priorities. Advancements in operational forecasts, predictions, and projections cannot occur without sustained investment in NOAA's HPC resources. Meeting NOAA's mission requires a sustained growth and balance of operational HPC and R&D HPC. Both systems are required to

	maintain an effective and evolving program that is capable of delivering model-based products important to the Nation today and into the future.
Commercial Space Activities Assessment Process	NESDIS seeks efficient solutions to address NOAA's need to measure key environmental phenomena from space. To meet these needs, NOAA integrates international, intergovernmental, and commercial capabilities, when practical, with NOAA's own satellites into its global satellite observing system. This report outlines the process NESDIS will follow to implement the NOAA Commercial Space Policy ("NOAA Policy"), including establishing a process by which NESDIS will assess and pursue commercial opportunities to support NOAA's space-based observational information requirements.
The NOAA's Report on Requiring the TsunamiReady® Program to be accredited by the Emergency Management Accreditation Program	The Emergency Management Accreditation Program (EMAP) is an independent, non-profit organization that oversees a very specific program through which all-hazard emergency management programs are accredited. The NWS TsunamiReady® program is not a comprehensive emergency management program, and is neither authorized nor appropriated to conduct the EMAP activity. The report expresses the comprehensive EMAP process is well beyond the scope of the NWS mission; would require new legislative authority for NWS to administer an EMAP; and would conflict and overlap with other Federal agency (Federal Emergency Management Agency (FEMA)) authority, and local government responsibility.
NOAA Commercial Space Policy	NOAA seeks to leverage commercial space capabilities to capitalize on available extramural expertise, to improve weather forecasting, diversify NOAA's portfolio of data collection capabilities, to promote U.S. space commerce and the industrial base, and to pursue enhancements in mission areas, program schedules, and costs.
Operations and Workforce Analysis Catalog	This catalog details findings and ideas generated during the Operations and Workforce Analysis (OWA) from May 2015 to December 2016, designed to assess NWS current operations and its workforce. The catalog includes responses to recommendations from the National Academy of Sciences and the National Academy of Public Administration, which were supported by Congress.
Study: Gaps in NEXRAD Radar Coverage	Tornado events from the NWS verification database are examined for the period 2006-2017 against radar coverage, the latter binned in terms of events inside and outside the range implied by the 6000 ft. above ground level (AGL) bottom-of-the-beam at each of the NEXRAD radars. In addition, radar coverage is separately

	quantified by the percent surface areal coverage at each NWS Weather Forecast Office. Fatalities and injuries are quantified along with NWS performance metrics in terms of radar coverage and geographical characteristics, with relative parity between the percentages of tornado events warned or unwarned inside and outside of the selected range.