REPORT TO CONGRESS

HURRICANE FORECAST IMPROVEMENT PROGRAM

Developed pursuant to Title I, Section 104 of the Weather Research and Forecasting Innovation Act, 2017 (P.L. 115-25)

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TITLE I, SECTION 104 OF THE WEATHER RESEARCH AND FORECASTING INNOVATION ACT, 2017 (Public Law (P.L.) 115-25) INCLUDED THE FOLLOWING LANGUAGE

(a) IN GENERAL. – The Under Secretary, in collaboration with the United States weather industry and such academic entities as the Administrator considers appropriate, shall maintain a project to improve hurricane forecasting.

(b) GOAL. – The goal of the project maintained under subsection (a) shall be to develop and extend accurate hurricane forecasts and warnings in order to reduce loss of life, injury, and damage to the economy, with a focus on –

(1) improving the prediction of rapid intensification and track of hurricanes;

(2) improving the forecast and communication of storm surges from hurricanes; and

(3) incorporating risk communication research to create more effective watch and warning products.

(c) PROJECT PLAN. – Not later than one year after the date of the enactment of this Act, the Under Secretary, acting through the Assistant Administrator for Oceanic and Atmospheric Research and in consultation with the Director of the National Weather Service (NWS), shall develop a plan for the project maintained under subsection (a) that details the specific research, development, and technology transfer activities, as well as corresponding resources and timelines, necessary to achieve the goal set forth in subsection (b).

THIS REPORT RESPONDS TO THE CONGRESSIONAL REQUIREMENT.

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Executive Summary

The Hurricane Forecast Improvement Program (HFIP) began in 2009 and has significantly improved forecast performance for the last 10 years, while meeting the five-year goal to reduce track and intensity errors by 20 percent. Much remains to be done although the improvements are notable. The Bipartisan Budget Act of 2018 (PL 115-123) provided $50 million for operational and research and development (R&D) high performance computing (HPC) at the National Oceanic and Atmospheric Administration (NOAA), which will be shared between NOAA's Office of Oceanic and Atmospheric Research (OAR) and the National Weather Service (NWS). This funding will extend NOAA's current computing capacity, including efforts related to HFIP, for the next three to four years. In addition, HFIP receives approximately $13.5 million in annual funding (Table 1), which directly supports the strategies listed in Table 2. The next generation of HFIP will continue its mission to reduce impacts of hurricanes through the implementation of these key strategies designed to improve forecasts and warnings, while achieving the NWS goal of building a Weather-Ready Nation. OAR and NWS will continue to address existing science and research-to-operations (R2O) challenges by improving regional and global models; transitioning promising innovations from research to operations; and partnering with academia, America's Weather Industry[1], and the emergency response community to achieve the objectives outlined for the next generation of HFIP, successfully addressing the requirements of Title I, Section 104 of the Weather Research and Forecasting Innovation Act of 2017 (P.L. 115-25). Continued annual appropriations at the currently requested level will continue improvements described in this plan.

Table 1: NOAA Funding for HFIP Activities under Section 104 of the Weather Act
(Dollar Amounts in Thousands)

Subactivity Program, Project, or Activity	**FY19 President's Budget**	**FY20 President's Budget**
Office of Oceanic and Atmospheric Research (OAR)		
Laboratories & Cooperative Institutes (ORF)*	$5,900	$5,900
U. S. Weather Research Program (ORF)	$1,000	$1,000
National Weather Service (NWS)		
Science and Technology Integration (ORF)	$4,500	$4,500
Central Processing (PAC)**	$2,000	$2,000

* ORF represents funds specifically allocated for *operations, research, and facilities*
** PAC represents funds specifically allocated for *procurement, acquisition, and construction*

[1] America's Weather Industry includes all elements of the private sector (e.g., media, consultants, equipment providers, etc.), which provides services to the public in the areas of climate, water, and weather. The term may include foreign-owned companies that provide services to the American public.

1. Introduction

This project plan is in response to Title I, Section 104(c) of the Weather Research and Forecasting Innovation Act of 2017 (P.L. 115-25 or the Weather Act), passed into law by Congress on April 18, 2017.

Title I, Section 104 of the Weather Act includes the following language:

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2. Background

Hurricanes pose a recurring threat to much of the U.S. coastline. For example, 27 named tropical storms and 13 hurricanes crossed U.S. coastlines between 2000 and 2010. In response to particularly deadly and/or damaging hurricanes in the first half of that decade[2] (i.e., Charley, Frances, Ivan, and Jeanne in 2004; Katrina, Rita, and Wilma in 2005), HFIP was established as part of NOAA in 2009.

HFIP is designed to accelerate the development and implementation of promising technologies and techniques from the research community into operations. This approach resulted in a 20 percent reduction in errors from numerical guidance for both storm track and intensity within the first five years of the program (see Fig. 1). However, such improvements leveled off after 2015, suggesting that HFIP R&D, which focuses on forecast outliers and rapid intensification events, is needed to reach the program's original 10-year goals. Additionally, to better communicate risks to the public and the emergency management community, HFIP invested in social science research contributing to the development and implementation of operational storm surge products, such as the Potential Storm Surge Flooding Map.

[2] https://journals.ametsoc.org/doi/full/10.1175/BAMS-D-12-00071.1

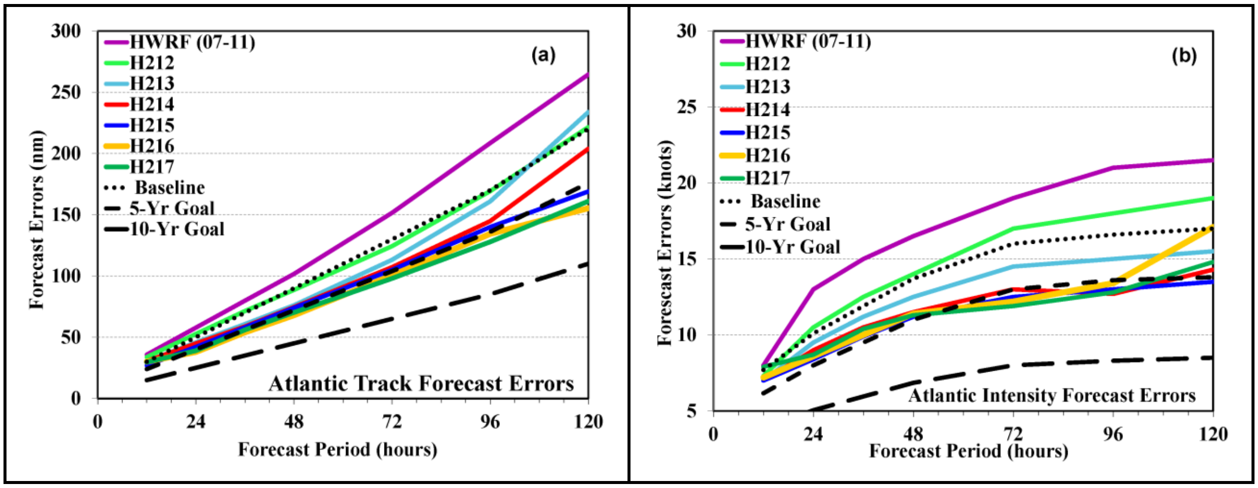

Figure 1: Hurricane Weather Research and Forecast (HWRF) Model improvements in forecast track (a) and intensity (b) error for the Atlantic Basin from 2007-2011 and annually through 2017 under HFIP are shown. Seasons for which models were run are depicted on each line. Note that some samples (years) are not homogeneous between models.

HFIP provides the unifying organizational infrastructure and funding for NOAA and other agencies to coordinate the research needed to significantly improve guidance for tropical cyclone (TC) track, intensity, and storm-surge forecasts, as well as accelerate the transition of R2O. HFIP focuses multi-organizational (e.g., NOAA, National Centers for Atmospheric Research, U.S. Navy, National Aeronautics and Space Administration, Federal Emergency Management Agency, and Joint Center for Satellite Data Assimilation) activities to research, develop, demonstrate, and implement enhanced operational modeling capabilities, dramatically improving the numerical forecast guidance made available to the National Hurricane Center. Furthermore, through public-private partnerships with organizations such as Northrop Grumman, Northwest Research Associates, and the National Center for Atmospheric Research, HFIP facilitates the development of the next generation of TC researchers for NOAA. These benefits will continue under the next generation of HFIP.

Tracking the progress of numerical TC prediction guidance through HFIP activities to date has shed light on the key strategies that deliver the most significant results and areas into which HFIP's focus should be extended. HFIP has also identified the need for more meaningful ways to measure progress for high-impact events (e.g., rapid intensification). Forecast challenges during the 2017 hurricane season underscored the need to address issues, such as rapid intensification, genesis, storm size, and rainfall, as demonstrated by Hurricane Harvey in Texas. Hurricane Irma highlighted a need for improvements in forecasting track, storm size, and storm surge. Hurricane Maria, devastating to Dominica and Puerto Rico, again pointed to a need to better predict genesis and rapid intensification, as did Hurricanes Matthew (2016), Joaquin (2015), and Patricia (2015).

To improve TC forecasting with the goal of developing and extending accurate TC forecasts and warnings in order to reduce loss of life, injury, and damage to the economy, the next generation of HFIP will focus on:

- Improving the prediction of rapid intensification and track of TCs;
- Improving the forecast and communication of surges from TCs; and
- Incorporating risk communication research to create more effective watch and warning products.[3]

This project plan, as required by Section 104(c) of the Weather Act, details the specific research, development, and technology transfer activities associated with HFIP's science and R2O challenges. Some key challenges include: 1) reducing Hurricane Weather Research and Forecast Model (HWRF) forecast guidance errors associated with rapid intensification; 2) reducing global modeling guidance errors to extend forecasts to seven days; 3) improving utilization of high-resolution ensembles for model initialization and in product generation; 4) better utilization of satellite observations in cloudy regions surrounding tropical cyclones; and 5) better utilization of all observation platforms (i.e., satellite, ocean, aircraft) to improve intensity forecasts.

3. Goals

In order to address the three primary focus areas outlined above, HFIP has a set of specific goals and metrics to improve the accuracy and reliability of TC forecasts and warnings and increase the confidence in those forecasts to enhance mitigation and preparedness decisions by emergency management officials.

The next generation of HFIP will build upon the original goals of the program[4] through the following specific goals:

- Reduce numerical forecast guidance errors,[5] including during rapid intensification, by 50 percent from 2017;
- Produce seven-day forecast guidance that is similar to the 2017 five-day forecast guidance;
- Improve guidance on pre-formation disturbances, including genesis timing, and track and intensity forecasts, by 20 percent from 2017; and
- Improve hazard guidance and risk communication, based on social and behavioral science, to modernize the TC product suite (i.e., products, information, and services) for actionable lead times for storm surge and all other threats.

4. Key Strategies

To meet these goals, six key strategies are described below that will continue improving track and intensity guidance, particularly for rapid intensification, and extend the focus to improving guidance on storm size, storm surge, and all other TC hazards at actionable lead times (e.g., 48-72 hours, depending on the hazard). Improved hazard guidance will derive from development of a hurricane analysis and forecast system: 1) producing ensemble guidance; 2) enabling probabilistic hazard products; and 3) improving track, intensity, and storm size predictions before formation and throughout the storm's life cycle. Using social and behavioral science research, HFIP will design a more effective TC product suite to better communicate risk and

[3] As indicated in Section 104 of the Weather Research Forecasting and Innovation Act of 2017 (P.L. 115-25)
[4] http://www.hfip.org/
[5] Percent improvement is determined by evaluating track, intensity, storm size, and rapid intensification error relative to those over the three-year period, 2015-2017

apply it to all current TC hazards products. Success depends on continued support for development, R2O, and infrastructure (including high-performance computing), while continuing engagement with the larger academic community.

A. Advance an operational Hurricane Analysis and Forecast System

One of the biggest successes achieved during HFIP was the creation of the high-resolution HWRF system. The HWRF system – with further advancements in data assimilation techniques and better use of hurricane observations – will be the starting point for the first version of the Hurricane Analysis and Forecast System (HAFS). HAFS will be a multi-scale model and data assimilation package capable of providing analyses and forecasts of the inner core structure of the TC out to seven days. This capability is critical to improving size and intensity – including rapid intensification – predictions as well as improving the prediction of the surrounding large-scale environment that influences the TC's motion. HAFS will provide hurricane forecasters with reliable, robust, and skillful guidance on TC track, genesis, storm surge, rainfall, and tornadoes associated with TCs. It also will provide an advanced analysis and forecast system for cutting-edge research on modeling, physics, data assimilation, and coupling to earth system components for high-resolution TC predictions within the outlined Next Generation Global Prediction System/Strategic Implementation Plan objectives of the Unified Forecast System (UFS).[6]

B. Improve probabilistic guidance

HFIP will produce improved, actionable guidance that quantifies uncertainty for all TC hazards, including storm surge, and the development of advanced probabilistic forecast techniques will enhance that effort. R&D in this area will utilize a robust combination of physical, social, and behavioral science research. Current deterministic and probabilistic guidance will be improved through physical science research, supporting improved track, intensity (including rapid intensification), and size predictions before formation and throughout the storm's life cycle. As a framework for success in these efforts, HFIP plans to utilize the Forecasting a Continuum of Environmental Threats (FACETs)[7] framework as an overarching strategy to guide this transition of the TC hazard guidance.

C. Enhance communication of risk and uncertainty

HFIP plans to build upon the success in the Potential Storm Surge Flooding Map and Storm Surge Watch/Warning Graphic to more fully incorporate the social and behavioral sciences into the development and/or assessment of the TC products, information, and services for all hazards. Social and behavioral science research will leverage this improved guidance to facilitate a more effective TC product suite to better communicate risk and uncertainty for emergency managers and the public. Iterative, collaborated physical, social, and behavioral science research will then expand and refine this effort in order to reach the end goal of a full suite of products that are optimized to result in the maximum benefit to society for all TC hazards (e.g., storm surge, rain, associated tornadoes, gusts as well as sustained winds). HFIP will support social and behavioral science research to communicate TC risk and uncertainty by assessing partner and stakeholder

[6] As part of the UFS, defined by the NOAA Strategic Implementation Plan (2017) (https://www.weather.gov/media/sti/nggps/SIP-FY18-20-v4.pdf

[7] FACETs utilizes high-resolution probabilistic hazard information from a numerical model ensemble prediction system and is driven by scientific tools optimized for user-specific decision making through the integrated application of social and behavioral sciences (https://www.nssl.noaa.gov/projects/facets/).

information needs. This will include characteristics of that information, including physical science (e.g., risk, confidence, uncertainty, etc.), technological (formats, interactivity), and messaging (e.g., graphics, interactive, apps, etc.) parameters to effectively modernize the TC product suite.

D. Support dedicated high performance computing allocation

Since a larger community with key academic partners included is needed in TC model testing and evaluation, HFIP's strategy was to develop a dedicated R&D high-performance computing (HPC) allocation.[8] This led to the establishment of HFIP's Jet HPC system dedicated primarily to TC research, including a three-month demonstration phase during hurricane season. The availability of dedicated computing resources for TC R&D eliminates competition with other high-priority computing needs across NOAA's broad programs. The dedicated NOAA HPC allocation will be used to further improve TC predictions, placing priority on development, testing, and evaluation of the HAFS system and high-resolution ensembles for more accurate, timely, and effective guidance on all TC hazards. Moving forward, HFIP, as well as other NOAA research and modelling activities, will consider cloud computing strategies to utilize increased compute power, allocation, and potentially lower costs.

E. R2O Enhancement

The transfer of research to operations requires robust interaction between the research and operational community, as well as a strong interface with the user community. It also requires a healthy infrastructure for the transition, which would include resources and processes for evaluation and demonstration, operational implementation, and operations and maintenance. HFIP will continue to accelerate the transition of research and new observing systems and platforms to operations by adhering to the NOAA Administrative Order 216-105B, *Policy on Research and Development Transitions,* in assessing the maturity of R&D projects from R2O via Readiness Levels, developing and maintaining transition plans, and utilizing NOAA's Testbeds and Proving Grounds.[9]

HFIP will establish R2O activities within the Joint Hurricane Testbed (JHT), broadening the JHT charter by increasing support for HAFS and social and behavioral science R&D. HFIP proposes to develop interactions between JHT, Hydrometeorological Testbed (HMT), Hazardous Weather Testbed (HWT), Developmental Testbed Center (DTC), Joint Center for Satellite Data Assimilation (JCSDA), and Quantitative Observing System Analysis Project (QOSAP) to address HAFS R&D.

F. Broaden expertise and expand interaction with external community

HFIP envisions enhancing its TC-related research approach and expertise through its Scientific Review Committee. The Scientific Review Committee is composed of representatives from NOAA and the external R&D community that provide insight, independent evaluation and scientific direction in regards to the various projects that HFIP supports. HFIP will also reinvigorate its grants and contracts program to support R&D and training activities for external

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[8] Since 2009, NOAA dedicated $32 million (approx. $4 million per year) to HFIP to increase capacity and the maintenance of research and development HPC for TCs. From 2009 through 2016, annual expansions, by way of incremental hardware procurements, resulted in the Jet HPC system based in Boulder, Colorado, totaling 45,000 processors and 4.4 Petabytes of storage.

[9] http://www.corporateservices.noaa.gov/ames/administrative_orders/chapter_216/Handbook_NAO216-105B_03-21-17.pdf

community at NOAA operational facilities. Finally, HFIP will continue outreach and education for operational model development activities through workshops, conferences, and publications for internal and external reviews on HFIP priorities and progress.

5. Strategy Priorities and Objectives

The table below lists priorities and objectives for the next generation of HFIP, categorized by each of the six strategies, to support the overarching goals listed above. The details of funding requirements and timelines for each activity listed in the table are being developed within NOAA and are contingent upon resource availability. A fully supported plan will achieve the following objectives:

Table 2: Priorities and Objectives for Strategy Implementation

Strategy: Advance an operational hurricane analysis and forecast system (HAFS)	
Priorities ▪ R&D for HAFS to advance deterministic and ensemble prediction capabilities to 7 days ▪ R&D for fusion of modeling, data assimilation, and observations to produce an analysis of record ▪ R&D for statistical post-processing to extract guidance and uncertainty information	**Objectives** ▪ Annual upgrades to HAFS implemented operationally prior to transition to UFS ▪ Targeted data assimilation improvements for HAFS prior to transition to UFS ▪ Produce forecast track and intensity guidance to 7 days based on HAFS ▪ Complete demonstration of impact of forecast performance using the HAFS based on UFS ▪ HAFS based on UFS implemented operationally
Strategy: Improve probabilistic guidance	
Priorities ▪ Calibrate guidance with HAFS ▪ Incorporate dynamically-based uncertainty into hazard models and products ▪ R&D for hazard-specific products from HAFS	**Objectives** ▪ Test and evaluate high-resolution ensemble model for use in generating probabilistic guidance on track, intensity, and structure for use in improved storm surge and other hazard guidance ▪ Increase lead time of real-time storm surge guidance and forecasts from 2 to 3 days before the arrival of surge and wind hazards

	▪ Expand real-time storm surge forecasting capabilities to areas outside of the contiguous United States, including the Storm Surge Watch/Warning ▪ Create a Probabilistic Tropical Quantitative Precipitation Forecast product using HAFS output ▪ Perform a systematic evaluation of dynamical model forecasts for wind gusts associated with TCs
Strategy: Enhance communication of risk and uncertainty	
Priorities ▪ Evaluate TC products for the effective communication of risk ▪ Determine operationally viable ideas collected from NWS partners and stakeholders ▪ Iterate between social and behavioral sciences and operational community to develop and/or enhance new and/or current TC products	**Objectives** ▪ Conduct baseline assessment of NWS TC product suite for effective communication of risk and prioritize those products informed by social and behavioral science ▪ Modernize TC product suite based on the baseline assessment and prioritization ▪ Collect longitudinal data from users to ensure increased efficacy as product modernization occurs ▪ Gather NWS partner and stakeholder feedback on product changes
Strategy: Support Dedicated HPC Allocation	
Priorities ▪ NOAA R&D and operational computing to support HAFS development ▪ Sustain modeling and software engineering expertise ▪ Match technological innovations (i.e., keep pace with new technologies)	**Objectives** ▪ Staffing and computing infrastructure established to test and evaluate HAFS improvements and generating probabilistic guidance ▪ Evaluate and implement a cloud-computing approach to test and evaluate HAFS improvements and generating probabilistic guidance

<table>
<tr><th colspan="2">Strategy: R2O Enhancements</th></tr>
<tr><td>Priorities
▪ Accelerate R2O using NOAA Testbeds by following NOAA’s best practices for promoting readiness levels
▪ Develop a process to prioritize research targeted for operational improvements</td><td>Objectives
▪ Staff and infrastructure established for enhanced R2O
▪ Involvement with external community for modeling R&D through JHT, HMT, HWT, DTC, and JCSDA</td></tr>
<tr><th colspan="2">Strategy: Broaden expertise and expand interaction with external community</th></tr>
<tr><td>Priorities
▪ Re-invigorate the grants program
▪ Maintain a visiting scientist program at research and operational centers
▪ Maintain advisory committees and community workshops
▪ Collaborate/coordinate with social and behavioral sciences
▪ Outreach to America’s weather industry</td><td>Objectives
▪ Broaden community expertise through visiting scientists at research and operational centers
▪ Conduct workshop with social, behavioral, and physical scientists to assess operational viability of partner and stakeholder needs
▪ Partner with key agencies and professional organizations to ensure effective training and outreach
▪ Partner with America’s Weather Industry to disseminate and/or develop improved NWS TC products conveying risk or uncertainty</td></tr>
</table>

6. Summary

HFIP has significantly improved forecast performance over the past 10 years, reducing errors in track and intensity forecasts and extending reliable forecasts; however, much remains to be done. The next generation of HFIP will continue its mission to reduce impacts of hurricanes through the implementation of goals and strategies designed to improve forecasts and warnings in preparation of a weather-ready Nation. NWS and OAR will continue to address existing science and R2O challenges by: improving regional and global models, transitioning promising innovations from research to operations, and partnering with academia, America’s Weather Industry, and the emergency response community to achieve the objectives outlined for the next generation of HFIP, which will also successfully address the requirements of Section 104 of the Weather Act.

List of Acronyms

DTC	Developmental Testbed Center
FACETs	Forecasting a Continuum of Environmental Threats
HAFS	Hurricane Analysis Forecast System
HFIP	Hurricane Forecast Improvement Program
HMT	Hydrometeorological Testbed
HWRF	Hurricane Weather Research and Forecast Model
HWT	Hazardous Weather Testbed
JCSDA	Joint Center for Satellite Data Assimilation
JHT	Joint Hurricane Testbed
NOAA	National Oceanic and Atmospheric Administration
NWS	National Weather Service
OAR	Oceanic and Atmospheric Research
QOSAP	Quantitative Observing System Analysis Project
R&D	Research and Development
R2O	Research to Operations
TC	Tropical Cyclone
UFS	Unified Forecast System

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