NOAA Science Advisory Board Report

Environmental Information Services Working Group Report and Recommendations to the NOAA Science Advisory Board concerning the Hurricane Forecast Improvement Program

October 2020

PUBLIC LAW 115–25—APR. 18, 2017
The Weather Research and Forecasting Innovation Act

TITLE 1, SEC. 104. HURRICANE FORECAST IMPROVEMENT PROGRAM.

(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 1 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, 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).

EXECUTIVE SUMMARY

BACKGROUND

This report presents a review of NOAA's December 2019 *Report to Congress, Hurricane Forecast Improvement Program* (hereafter *HFIP Report*) by the Environmental Information Services Working Group (EISWG), an advisory working group reporting to the NOAA Science Advisory Board. Guidance for this effort includes:

- **Committee Charge:** EISWG is charged by Congress with reviewing NOAA HFIP reports submitted to Congress in response to the Weather Act, Title I, Sec. 104.
- **Approach:** To ensure that the review provides the most value to Congress and to NOAA, EISWG: (a) also referred to the *Hurricane Forecast Improvement Program Five-Year Plan: 2019-2024* (hereafter *HFIP Plan*) for details in addition to the *HFIP Report*, (b) requested and received an HFIP briefing from NOAA, and (c) consulted with external Subject Matter Experts (Appendix 2).

EISWG REVIEW RESULTS

To achieve the increasingly urgent goals of the Weather Act in a reasonable time, NOAA will need to continue to support HFIP, plus: (1) invest in additional physical, social and behavioral science research, motivated and targeted by an expanded set of success metrics; (2) leverage scientific and technological advances enabled by other line offices, testbeds, agencies, organizations and industry; and (3) entrain a broader network of expert personnel external to NOAA for convergent research and workforce development.

- **Weather Act Subsection (c): Project Plan Overall Responsiveness (SECTION 1)**

  Summary Findings: The primary role of HFIP since 2009 has been to identify and rapidly transition promising research to operations. The HFIP Report describes an expanded scope prompted by Weather Act goals without a change in budget.

  Summary Recommendation (1): To address The Weather Act Title 1, Sec. 104 (c), the expanded scope must be mapped to necessary resources and timelines.

- **Weather Act Focus (b)(1): Prediction of Rapid Intensification and Track (SECTION 2)**

  Summary Findings: Forecasting intensity change remains a coupled atmospheric-ocean modeling challenge that includes still uncertain physics and the need for continually-improved data assimilation. The Hurricane Analysis and Forecast System (HAFS) provides an environment for testing new developments.

Summary Recommendation (2): Expand participation through dedicated science campaigns that cross the atmosphere-ocean interface to improve model physics and data assimilation and increase the use of probabilistic forecasts to quantify uncertainty. Continue HAFS development and entrain more external researchers.

- **Weather Act Focus (b)(2): Forecast and Communication of Storm Surge (SECTION 3)**

Summary Findings: HFIP ties storm surge improvements to advances in the hurricane forecasts that drive the storm surge models, not the models themselves. NOAA-supported social science research has led to successful storm surge warning products, yet gaps remain in current communications strategies.

Summary Recommendation (3): Communicating storm-surge risk should be prioritized and account for uncertainty from multiple sources and address diversities of human perception, behavior, and needs. Evaluation and improvement of operational storm surge models should also be prioritized.

- **Weather Act Focus (b)(3): Risk Communication Research (SECTION 4)**

Summary Findings: HFIP notes the marked improvements from social/behavioral research on storm-surge flood maps and provides general plans to incorporate social/behavioral research on a suite of products, but the report lacks detail on how the advances will be achieved. Quantitative measures of success for risk communication research are lacking.

Summary Recommendation (4): Severe weather can evoke subsequent hazards; warning and watch products need to address risk from multiple threats. Developing a strategic plan for social and behavioral research with milestones and metrics should be a high priority to ensure forecasts and forecast products address diverse societal needs and impacts.

- **Partnerships & Collaborations (SECTION 5)**

Summary Findings: The need for improved hurricane forecasts is urgent. Physical, social and behavioral sciences, as well as observation and modeling technology, are advancing across government, academic and industry sectors, while NOAA budgets are increasingly constrained. Broader coordination, internally across OAR, NWS and NOS, and externally across government, academic and industry sectors, will be required to support targeted research motivated by operational needs.

Summary Recommendation (5): Increase internal coordination across OAR, NWS, and NOS and expand science and technology partnerships to achieve Weather Act goals.

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Committee Charge

The Weather Research and Forecasting Innovation Act of 2017 affirmed and authorized the NOAA Science Advisory Board (SAB) Environmental Information Services Working Group (EISWG) as a standing working group of the SAB and assigned additional, specific charges to the working group. These include:

1) To provide advice for prioritizing weather research initiatives at NOAA to produce real improvement in weather forecasting;
2) To provide advice on existing or emerging technologies or techniques that can be found in private industry or the research community that could be incorporated into forecasting at the NWS to improve forecasting skill;
3) To identify opportunities to improve (A) communications between weather forecasters, Federal, State, local, tribal and other emergency management personnel, and the public; and (B) communications and partnerships among NOAA and the private and academic sectors

EISWG organized the *HFIP Report* review Subpanel with four members: Scott Glenn (HFIP Subpanel Chair), Ann Bostrom, May Yuan and Brad Colman (EISWG Co-Chair). The Subpanel review incorporates advice from six external Subject Matter Experts (Appendix 2) to broaden its expertise as required.

The Urgent Need for Action

The need for improved hurricane forecasts and warnings is already critical and increasing. Total U.S. monetary damages from hurricanes and tropical storms since 1980 are now approaching $1 Trillion, more than all other billion dollar U.S. weather and climate disasters combined.[1] The resulting hurricane and tropical storm fatalities total over 6,500, more than any other single category of billion dollar weather and climate disaster. NOAA research has established a statistically significant trend that hurricanes are growing more severe,[2] and that the sea level baseline for destructive storm surge is rising at an accelerating rate.[3,4] U.S.

[1] https://www.ncdc.noaa.gov/billions/

[2] Kossin, James P. , Kenneth R. Knapp, Timothy L. Olander, Christopher S. Velden (2020). Global increase in major tropical cyclone exceedance probability over the past four decades. Proceedings of the National Academy of Sciences, 117 (22) 11975-11980; DOI:10.1073/pnas.1920849117;
Emanuel, Kerry (2020). Evidence that hurricanes are getting stronger, Proceedings of the National Academy of Sciences, 117 (24) 13194-13195; DOI: 10.1073/pnas.2007742117

[3] Kopp, R. E. (2020). Sea Level Rise, 1970–2070: A View from the Future. Earth 2020: An Insider's Guide to a Rapidly Changing Planet.

[4] Sweet, W. V., R. Horton, R. E. Kopp, A. N. LeGrande, and A. Romanou (2017). "Sea level rise". In: *Climate Science Special Report: Fourth National Climate Assessment, Volume I*. Ed. by D. J. Wuebbles, D.

states and territories impacted by hurricanes represent half the U.S. population.[5] Improved hurricane forecasts, communication of public risk, and warnings with increased accuracy and lead times are increasingly required to save lives, minimize damage, and protect the livelihoods of vulnerable populations.

The Weather Act of 2017 requires NOAA to develop and submit to Congress a Project Plan to improve hurricane forecasts and warnings, and for the NOAA Science Advisory Board (SAB) Environmental Information Services Working Group (EISWG) to review that plan. NOAA's response submitted in December 2019 is the document titled *Report to Congress, Hurricane Forecast Improvement Program (*abbreviated throughout as the *HFIP Report)*.

NOAA's Hurricane Forecast Improvement Program (HFIP) has been a cornerstone of the U.S. response to the Congressionally recognized need for improved hurricane forecasts and warnings since 2009. HFIP's key role has been to foster the transition of promising hurricane research into weather forecasting operations. The SAB and EISWG commend NOAA, HFIP, and its many external partners for all that has already been accomplished. Based on our review, the SAB & EISWG hereby deliver a list of Findings and Recommendations to help identify and accelerate progress in areas of key need.

Approach to this Review

EISWG is charged with reviewing and providing comments on NOAA's *Report to Congress, Hurricane Forecast Improvement Program (*hereafter *HFIP Report*). The report is justifiably complex. Starting with 1 goal and 3 Congressional focus areas, the *HFIP Report* identifies 5 challenges, 4 new metrics, and 6 key strategies, each with 3-5 priorities and 4-5 objectives (see Appendix 1).

To ensure that the review provides the most value to Congress and to NOAA, EISWG took several information gathering steps beyond relying solely on the primary document. Specifically:

1) EISWG noted that the 15-page NOAA *HFIP Report* submitted in 2019 is a summary document that is similar in structure to the more detailed 83-page *Hurricane Forecast Improvement Program Five-Year Plan: 2019-2024*, subtitled *Proposed Framework for Addressing Section 104 of the Weather Research and Forecasting Innovation Act of 2017,* originally dated 22 June 2018 and updated 25 June 2019, hereafter referred to as the *HFIP Plan*. The longer 83-page document addresses many of the "requests for

W. Fahey, K. A. Hibbard, D. J. Dokken, B. C. Stewart, and T. K. Maycock. Washington, DC, USA: U.S. Global Change Research Program. Chap. 12, pp. 333–363. doi: 10.7930/J0VM49F2.

[5] Estimated July 1, 2019 population totals from https://www.census.gov/quickfacts/fact/map/US/PST045219. Hurricane impacted states and territories here include: PR, TX, LA, MS, AL, FL, GA, SC, NC, VA, MD, DE, PA, NJ, NY, CT, RI, MA, VT, NH, ME, HI.

details" questions EISWG developed based on an initial read of the shorter 15-page *HFIP Report*.

2) EISWG requested and received briefings from the HFIP Research Lead. The EISWG sub-panel also took every advantage of additional public presentations on HFIP during the review process, to be as up to date as possible.
3) EISWG engaged key external Subject Matter Experts to further broaden its expertise and provide additional comments on specific aspects of the NOAA *HFIP Report*. The Subject Matter Experts were chosen for their world-class expertise in hurricane dynamics, hurricane forecasting, ocean impacts and air-sea interactions, storm surge, and risk communication with regard to extreme weather hazards. Subject Matter Experts (a) reviewed and provided independent comments on the NOAA *HFIP Report*, (b) met virtually with the EISWG subpanel to discuss their comments, and (c) reviewed and provided comments on the initial draft of the EISWG subpanel report that were incorporated before the report was submitted to the SAB.

EISWG used information gathered through these steps to provide here the compiled Findings and Recommendations on the NOAA *HFIP Report.* We note where findings are based on critical information beyond the NOAA *HFIP Report*. We further emphasize that it is important that this information gathering role for EISWG be recognized as vital to the success of this process, not only for our review of this Report to Congress, but also possibly others.

The EISWG report is divided into six sections. Section 1 provides overview comments on the *HFIP Report's* responsiveness to the overall Congressional request. Sections 2-4 provide extensive detailed comments on the *HFIP Report's* responsiveness to the three specific focus areas noted by Congress. Section 5 assembles comments on the critical need to expand partnerships to achieve the Weather Act goal. Each section begins with *Summary Findings* and *Summary Recommendations* statements (also noted in the Executive Summary), followed by specific *Findings* and *Recommendations* for each subsection topic. Section 6 is an overall summary.

SECTION 1: Is the HFIP report responsive to the Congressional request (c) overall?

Summary Findings: The primary role of HFIP since 2009 has been to identify and rapidly transition promising research to operations. The HFIP Report describes an expanded scope prompted by Weather Act goals without a change in budget.

Summary Recommendation (1): To address The Weather Act Title 1, Sec. 104 (c), the expanded scope must be mapped to necessary resources and timelines.

The *HFIP Report* lays out the general framework for responding to the Weather Research and Forecasting Innovation Act, Title I, Sec. 104. The *HFIP Report* sets specific goals relative to 2017 performance, and provides initial detail on the expanding research, development and transfer activities proposed in response. More extensive details on the proposed activities are found in the much longer *HFIP Plan.* HFIP developed a more compact but similar set of goals to guide its first decade of activities. Here we discuss the historical goals, the need for mapping the expanded scope to the timelines and resources required to achieve the new goals, and the clear need to develop a broader convergent strategy beyond present-day HFIP to be successful.

1.1 Historical Goals

Findings: HFIP began its work in 2009. Early rapid successes and achievement of the targeted 20% improvement in track and intensity forecast goals for the first 5 years of HFIP are documented in the *HFIP Report* and the most recent *HFIP Plan*. Progress during the second 5 years of HFIP was much slower, and both the *Report* and *Plan* indicate the 10 year targets of 50% track and intensity improvements were not achieved. A fundamental unanswered question in the *HFIP Report* is why the first 5 years were so successful, and what caused progress to level off during the second 5 years?

HFIP presentations suggest that achieving the first 5 year goals was enabled by the new higher-resolution regional HWRF model that better resolved the hurricane structure, and by the new marine boundary layer physics developed through collaborations with the Navy's CBLAST science campaign - a focus on new model development and field campaigns. The *HFIP Plan* further suggests that the ability to meet the 10 year target was diminished due to a reduction in funding (p. 53, under Requirements for Success), although the *HFIP Report* does not include this conclusion. Detailed appropriation history (provided in presentations) indicates that while OAR Operations, Research and Facilities support, has remained relatively steady since inception, other sustained sources of support dropped significantly in FY15 and again in FY17. Without Congressional supplemental funds, HFIP support for each of the most recent 5 years remains less than half of the historical highs during the first 5 years (Appendix 1).

Recommendation (1.1): As NOAA embarks on what is now the third 5-year increment for HFIP, the reasons for achieving the initial 5-year goals, followed by the lack of progress towards the 10-year goals, should be identified and used to further inform the current approach.

1.2 Scope, Resources and Timelines

Findings: The Weather Act requires submission of a "Project Plan" to "detail the specific research, development and technology transfer activities, as well as corresponding resources and timelines, necessary to achieve the goal…".

The *HFIP Report* presents additional metrics for measuring progress towards the Weather Act goal in Section 3, key strategies for research, development and technology transfer to achieve the metrics in Section 4, and the priorities and objectives of each key strategy in Table 2. The metrics and key strategies expand the historical scope of HFIP.

Available resourcing (it is important to note that this is not equivalent to the necessary resourcing requested by Congress) is only briefly summarized in the Executive Summary and its

Table 1. This includes: (a) annual allocations of $12.9 M that are currently available for FY19 and projected for FY20, (b) an additional $2 M in supplemental funds for FY19, and (c) $50 M in shared High Performance Computing (HPC) that includes an unspecified level of support for HFIP activities. This level of funding is consistent with the lower levels of support HFIP received when the 10 year targets were not met.

Timelines are not included for most of the activities or for achieving the new metrics. It is recognized that timelines are resource dependent (*HFIP Report* page 12). It currently appears that the only way to achieve the expanded scope with progress measured by the new metrics at this historically low level of support is through extended timelines and additional contributions by partners.

Recommendation (1.2): NOAA should explain how the increase in scope can be achieved within a reasonable time frame if the available funding remains at the same level. It is critical that strategic plans be developed and mapped to required resources and timelines.

1.3 Developing a Convergent Interdisciplinary and Integrated Approach

Findings: HFIP's focus on transitions between research and operations has been critical to its success and remains so. HFIP sets targets for what the transitions will achieve, such as improved hurricane track and intensity forecast metrics, and HFIP has plans, such as the Hurricane Analysis and Forecast System (HAFS), that will improve transition efficiencies even further. But if the required research is not available to transition, and there is insufficient capacity to implement HFIP-endorsed operational improvements, how can HFIP be accountable to the metrics?

Recommendation (1.3): Achieving the Weather Act goal will require broader NOAA coordination and integration of physical, social and behavioral scientific research, transition, and operational activities, all implemented in a strategic manner to address gaps with innovative convergent solutions. Requirements and resources, developed across the NOAA line offices of OAR, NWS and NOS, and with participation from the external community, are required to support targeted short-term to long-term research and technology development motivated by operational needs.

SECTION 2. Is the HFIP report responsive to the specific focus identified in (b)(1), "improving the prediction of rapid intensification and track of hurricanes" ?

Summary Findings: Forecasting intensity change remains a coupled atmospheric-ocean modeling challenge that includes still uncertain physics and the need for continually-improved data assimilation. The Hurricane Analysis and Forecast System (HAFS) provides an environment for testing new developments.

Summary Recommendation (2): Expand participation through dedicated science campaigns that cross the atmosphere-ocean interface to improve model physics and data assimilation and increase the use of probabilistic forecasts to quantify uncertainty. Continue HAFS development and entrain more external researchers.

Here we first briefly note the recognized persistent challenges of forecasting intensity change. The next three subsections address key forecast model guidance improvements to address current needs, including probabilistic forecasts, ocean data assimilation, and coupled atmosphere-ocean process parameterizations. We provide suggestions for an expanded metrics framework to assess progress, and three key approaches to foster advances, including: focused science campaigns, continuing to build the community testbed (i.e. HAFS), and establishing the data archive for research. We conclude with comments on the need for building and maintaining a diverse research team.

2.1 Addressing the Challenges of Forecasting Intensity Change and Track

Findings: Annual NWS statistics demonstrate steady improvement in track forecasts over the last two decades, with attribution including the general progress in global weather models. The growing ability of basin-to-global scale models to include multiple storms at high resolution is a significant advance. Improved forecasting of hurricane genesis, a component of HFIP's new metrics, will provide a new challenge to global/basin scale models where gaps in knowledge related to fundamental processes still exist.

The same NWS annual statistics indicate intensity forecast improvements have lagged, with deficiencies attributed to poor forecasts of outlier events that include Rapid Intensification (RI) or Rapid Weakening (RW). Within the continuous spectrum of intensity change rates, both RI and RW present forecasting challenges for existing operational models. RI events require the proper atmospheric conditions, as well as an ocean with sufficient heat content to provide the energy. Known challenges include forecasting rapid intensification of initially weak storms that have existed for some time, or storms embedded in the moderate range of atmospheric wind shear conditions. Conversely, rapid weakening can occur when the intense atmospheric forcing results in rapid co-evolution of the ocean and atmosphere, inducing mixing and cooling of the ocean surface layer that produces a negative feedback on intensity.

Recommendation 2.1: NOAA should articulate a vision for what longer-term research is required to achieve forecast improvements to intensity change and track. Within that vision, existing metrics already suggest that NOAA will need to include approaches to study hurricane genesis, the influence of wind shear, and coupled atmosphere-ocean physics. To accomplish this, it is recommended that NOAA more aggressively pursue dedicated observation and coupled model simulation studies in targeted research areas. HFIP is encouraged to continue expanding beyond improving annual mean track and intensity statistics to include more focus on the physics of outlier events as an additional path to improve all forecasts. One recommended approach is to bring together experts from the forecasting centers and the external community to evaluate challenging track and intensity forecasts from the previous year, and to collectively design the field and/or modeling studies that will enable challenging forecasts to be improved.

2.2 Expanding Probabilistic Forecasts

Findings: Reducing the uncertainty in hurricane track and intensity forecasts has historically emphasized generating the best possible deterministic real-time guidance with high resolution regional hurricane models. Forecasts of track and intensity are routinely provided out to 5 days. The *HFIP Report* proposes to extend reliable forecast durations to 6 and 7 days, but does not provide specific details on how this will be accomplished. To achieve more skillful extended-range track and intensity forecasts, improvements to ensemble based and statistical approaches may prove useful, prompting a growing emphasis on probabilistic approaches to quantify uncertainty. Increasing probabilistic guidance will require assembly of a multi-model ensemble with significant High Performance Computing (HPC) needs (also noted on p. 54 of the *HFIP Plan*), as well as establishing a balance between the small number of highest-resolution full-physics deterministic model runs, and the larger number of possibly lower-resolution reduced-physics model runs for the ensemble.

Recommendation (2.2): NOAA should provide a stronger plan on the research, development and testing needed to extend the track and intensity skill of deterministic model forecasts and of multi-model ensembles for probabilistic forecasts. Concurrently, and in an integrated effort, NOAA should also develop user-centric methods for characterizing, quantifying and visualizing this information for critical user groups, such as forecasters and emergency managers. Specifically, approaches to characterize and quantify uncertainty should be coordinated with risk communication research from the outset so that the information can be developed in ways that are most useful. NOAA should conduct the experiments to determine the proper balance between horizontal resolution and the number of ensemble members required to reliably extend forecast range. NOAA could further leverage Navy investments in their tropical cyclone ensemble to create a national multi-model ensemble for hurricanes. The Joint Hurricane Testbed structure could be leveraged as a potential forum for development, but this would require expanded support.

2.3 Advancing Ocean Model Data Assimilation

Findings: As of August 2020, both U.S. operational regional hurricane forecast models now use ocean initial conditions ultimately derived from the same data-assimilative global ocean model, the U.S. Navy's Global Ocean Forecast System (GOFS). Region-specific ocean features impacting hurricane intensity (e.g., the Loop Current/Gulf Stream boundary current and its eddies, surface freshwater barrier layers, bottom cold pool layers, etc.) have been identified through numerous OAR/NOS hurricane research programs outside of HFIP. Distributed near-real-time ocean observations provided to the data assimilative models can ensure that the essential ocean features are in place well before a hurricane arrives. Within this structure, NOS- and OAR-sponsored demonstration projects are proving the value of sustained ocean data collection with distributed autonomous systems for assimilation. NOAA is working to upgrade its ocean data assimilation capabilities by (a) adapting the Navy's operational ocean Data Assimilation (DA) system to the existing NOAA global Real Time Ocean Forecast System

(RTOFS) and is running it experimentally in 2020, and (b) implementing new DA procedures for the future Modular Ocean Model (MOM-6). What is learned by improving RTOFS DA will streamline development of DA procedures for MOM-6. Improved ocean data assimilation in the global models will benefit a wide variety of users beyond the hurricane community.

Recommendation (2.3): NOAA should expand Data Assimilation (DA) assessment procedures for ROTFS immediately, and MOM-6 eventually, to assess current implementations while the new DA procedures are still experimental. An assessment will require NWS to expand their DA team, something that can be efficiently accomplished by leveraging existing expertise in the research community. NOAA should support ocean-focused Observing System Experiments (OSEs) and Observing System Simulation Experiments (OSSEs) that leverage regional expertise available through the IOOS Regional Associations, and the OAR Laboratories and Cooperative Institutes, to refine the multi-platform observing system requirements. NOAA should seek cost-effective approaches for sustaining the observing system, such as applying the new NOAA Uncrewed Systems Strategy in ways that capitalize on the value of distributed autonomy already demonstrated in the NOAA Hurricane Glider community and previously shown from aircraft-based expendable and float technologies.

2.4 Improving Coupled Atmosphere-Ocean Process Parameterizations

Findings: Operational hurricane guidance products for the NHC forecasters are generated with regional-scale coupled atmosphere-ocean models that are sufficiently high resolution to resolve the storm. The coupled models then use parameterizations for even smaller scale unresolved processes that also impact intensity. The parameterizations include stratified deep and coastal ocean mixing processes, wave and spray generation, air-sea fluxes of heat, mass and momentum, atmospheric boundary layer processes and cloud microphysics. Multiple parameterizations are often available that can produce a wide range of results when applied outside the range of their original training datasets.

Dedicated observations are required to differentiate between existing parameterizations, to motivate improvements, and to demonstrate their impact on intensity and track forecasts. Especially lacking are: (a) ocean current profile data collocated with the more prevalent ocean temperature and salinity profiles in deep ocean and coastal environments to enable comparisons of Richardson number dependent mixing schemes; (b) in situ surface temperature, salinity and wave data to determine how surface conditions evolve during the hurricanes's direct forcing phase; (c) observations in the lower part of the atmospheric marine boundary layer, that in spite of the observational challenges, are required to better understand how the atmosphere interacts with a wavy and non-distinct ocean surface during intense forcing; and (d) observations in tropical cyclones of mixed phase (water and ice) and ice microphysics that are typically hazardous for the aircraft to carry out.

Recommendation (2.4): NOAA should sponsor both retrospective analysis of existing datasets and the collection of new measurements across the air-sea interface during tropical cyclone or similar conditions to differentiate and advance mixing and air-sea interaction parameterizations and their use in 3-D models. NOAA is encouraged to accomplish some of the observational goals with modifications to existing technologies, such as collocated ocean profile observations of temperature, salinity, currents, and turbulence structure, and broader coverage of surface salinity for large river plumes. NOAA will need to strengthen investments in the continued development of proven aircraft survey, air-deployed sensors, and autonomous systems that can make collocated observations across the air-sea interface in high winds, and also expand recent efforts to obtain microphysics measurements of the ice/mixed phase in clouds, in a safe manner. NOAA will need to support the continued scientific analysis of the data, and organize the parameterization studies informed both by data and by Large Eddy Simulations (LES). The NOAA Coastal and Ocean Modeling Testbed (COMT) should be added to the list of testbeds engaged by HFIP, and COMT, through its academic partners, could be expanded to develop an Ocean Forecast Improvement Program for hurricanes.

2.5 Expanded Metrics

Findings: Hurricane forecast metrics have a historical focus on track and intensity - output metrics derived from the numerical guidance or from the forecasters themselves. The *HFIP Report* sets specific targets for several additional forecast parameters (sections 3-4) relative to 2017 performance, but it is unclear if there is an established process to define the new output metrics. There has been much less emphasis on evaluating inputs to the forecast models and how the models represent physical processes in extreme wind forcing conditions. This makes it difficult to establish why a specific forecast was good or bad, and leaves open the possibility of getting the forecast right for the wrong reasons. Conventional metrics such as minimizing root mean square error will inherently underpredict extreme events such as the targeted RI or the also important RW. Models that do forecast RI or RW events but miss the timing by a small amount can be overly penalized by conventional metrics. With the exception of risk communication, which references improving hazard guidance and risk communication with actionable lead times for storm surge and all other threats but without specific targets, a focus on track, intensity and similar output metrics further neglects metrics on impacts. Very few probabilistic metrics are established in the hurricane forecasting community. Metrics require observations to evaluate the models, providing additional motivation for observation programs.

Recommendation (2.5): NOAA should leverage a broader range of observations and establish input metrics and internal process metrics for the hurricane forecast models that complement the established output metrics for track and intensity. These include specific critical components of the atmospheric forecast, the ocean forecast, and the air-sea coupling, for different types of processes and events. The effort should enable illumination of why some specific storm forecasts were good, and what caused other specific storm forecasts to stray. Probabilistic metrics can leverage Navy experience. Impact-based metrics should leverage the storm surge community experience and should be used to track progress towards outcomes.

2.6 Conducting the Science Campaigns

Findings: Major advances in hurricane forecasting are often traced to major multi-year scientific sampling and analysis campaigns. The Office of Naval Research (ONR) has funded multiple campaigns (e.g., CBLAST, TCI, TCS08, ITOP). Equally important, HFIP has successfully established its value for over a decade as the leader in the annual transition process. This structure for HFIP, combined with the relatively small scale of funding, necessarily emphasizes the incremental year-to-year advances with transitions timed to the approaching hurricane season.

Recommendation (2.6): It is recommended that NOAA strive to maintain both the proven annual heartbeat of HFIP transitions and the longer-term ONR-style research campaigns. Similar to the Tropical Cyclone Rapid Intensification experiment, where Navy and NOAA collaborators are sharing resources to observe key processes for RI, the campaign process should include coordination efforts within a research community that extends beyond NOAA to include the Navy, other agencies, academics, and the weather industry. A multi-platform sampling campaign should be targeted and coordinated to acquire critical observations pre-storm, during storm, and post-storm, to advance the understanding of hurricane physics in both deep and coastal ocean test cases that cover a broad range of hurricanes and regions. External researchers will require funding not normally available from pure research agencies.

2.7 Continue Building the Model Test Environment - HAFS

Findings: The Hurricane Analysis and Forecast System (HAFS) holds the same promise for the hurricane community as the Earth Prediction Innovation Center (EPIC) does for the global weather forecasting community. The *HFIP Report* states that HAFS will provide a research testbed for high resolution model simulations, data assimilation, model coupling, and physical process studies. The HAFS research testbed can also provide a hands-on training environment for future workforce development. Current external access to the operational hurricane forecasts is severely limited, requiring a NOAA Common Access Card (CAC) for even the simplest operational model-data comparisons in the atmosphere and ocean. The exact features HAFS will support, and when they will be available, are likely still being planned and are likely funding dependent. For example, atmospheric data assimilation is currently supported by the regional hurricane models, but all ocean data assimilation is conducted in the global domain. The *HFIP Plan* further states HWRF will be part of HAFS, since it will take several years for the new hurricane models based on the FV3 core to match the continuously advancing skill level of HWRF.

Recommendation (2.7): Continued development of HAFS is strongly encouraged. NOAA should rapidly broaden the research team by supporting open community access to HAFS, similar to EPIC. Additional R&D funds should be made available for priority projects, as well as allowing access to scientists and students not receiving direct NOAA support. Students should be encouraged to join the HAFS community to provide a pool of potential future NOAA employees. HAFS should include both the new experimental hurricane models based on the

FV3 core, but also the operational and experimental versions of HWRF and HMON. One critical aspect of HAFS is the stated potential for model coupling, that should include ocean, wave and storm surge models. Investigating rapid co-evolution of the atmosphere and ocean, model parameterizations, air-sea interactions, and storm surge impacts, requires testing in a coupled environment that should be included in the HAFS implementation.

2.8 Building the Distributed Data Archive

Findings: Hurricane datasets collected aboard the operational aircraft are increasingly valuable to researchers but can be difficult to access. Coupled atmosphere-ocean datasets required for model evaluation studies are rare. Collocated upper ocean current and density profiles to evaluate shear-induced mixing processes in high winds are extremely limited. Autonomous observation systems capable of sampling the atmospheric boundary layer close to the sea surface are under development and hold the promise of delivering new transformative data. Autonomous platforms not involved in hurricane research may still contribute valuable information if their datasets are shared, similar to the approach used in the IOOS Glider Data Assembly Center (DAC).

Recommendation (2.8): NOAA should establish and maintain a FAIR (findable, accessible, interoperable and reusable) distributed database of hurricane-relevant operational and research datasets to provide hurricane researchers and their students with scalable access for analysis and model/data comparisons. Enabling access to validation data is a cyber-infrastructure development process that should run in parallel with the development of the HAFS model testing environment.

2.9 Forming the Diverse Research Teams

Findings: The weather forecasting success of the European community is often linked to greater academic and industry involvement, with innovation tied to the greater flow of people with different backgrounds through the government system. Innovation is a core tenant of the Weather Act. HFIP Key Strategy F, *to broaden expertise and expand interaction with the external community*, indicates that this need is recognized. HFIP proposes to establish a Scientific Review Committee for the projects it supports, but HFIP funding is limited to less than $13M per year in base funding. HFIP proposes to reinvigorate an external grants program for R&D and training, but only $0.5M is dedicated to the Weather Research Program while $2M is dedicated to Central Processing. HFIP is self-described as the transition team to move promising research to operations for hurricanes, and has a proven record of success in this area. Current investments in HFIP do not match the research and innovation needs for improved hurricane forecasts and warnings. Since the research and eventual operations include both atmospheric and ocean components, the research teams will benefit from the experience within and contributions from all three line offices of OAR, NWS and NOS.

Recommendation (2.9): NOAA must broaden the research teams to accomplish the Weather Act goal. This can be more rapidly and efficiently achieved by actively entraining the community of dedicated hurricane researchers already available in the Navy, other agencies, academics and industry. Historic task teams should be renamed and reconstituted within this vision. New research and training with innovative technology should be focused on the targeted problems that still need to be solved.

SECTION 3. Is the HFIP report responsive to the specific focus identified in (b)(2), "improving the forecast and communication of storm surges from hurricanes" ?

Summary Findings: HFIP ties storm surge improvements to advances in the hurricane forecasts that drive the storm surge models, not the models themselves. NOAA-supported social science research has led to successful storm surge warning products, yet gaps remain in current communications strategies.

Summary Recommendation (3): Communicating storm-surge risk should be prioritized and account for uncertainty from multiple sources and address diversities of human perception, behavior, and needs. Evaluation and improvement of operational storm surge models should also be prioritized.

In this section we comment first on model improvements, not only for hurricanes approaching landfall, but also for the storm surge models themselves. We then comment on enhancing the communication of storm surge risk and uncertainty for the improved models. We conclude with suggestions supporting Research to Operations (R2O) transitions for hurricane storm surge forecasts and warnings.

3.1 Improved Models for Hurricanes Approaching Landfall and Storm Surge

Findings: Improving any forecast aims to provide actionable lead times and products for effective communication of weather hazards. Actionable lead times and products vary, depending on response needs for different hazards and stakeholders. To be actionable for evacuation[4] decisions, preparation and response planning, and emergency response execution, may require (a) communication of storm surges and risk further than 2 to 3 days in advance as currently planned, (b) communication of the time evolution of water level rise and fall rather than only the maximum water level, and (c) results that more closely reflect uncertainty in the current storm rather than a composite of historical storms. In addition to forecasting track and intensity, the size of a hurricane approaching landfall is essential to estimate the impacts of

[4] While some places also will need actionable information for shelter-in-place decisions in the case of storm surges, such as Hawaii, which has such guidelines for the 4th floor or above (http://www.honolulu.gov/site-dem-sitearticles/38999-hurricane-douglas.html), in most states emergency managers are likely to be concerned that suggesting sheltering in place for storm surge may produce noncompliance with evacuation advisories by people who are unrealistically optimistic about their home's elevation above sea level and its ability to withstand battering waves and debris.

induced storm surges. Effective risk communication requires attending to how and for whom actionable is being defined.

Improved storm surge forecasts require advances in hurricane forecasts (particularly storm track, intensity, and size) when a storm is approaching landfall, and advances in the storm surge models themselves. Considerable and diverse surge modeling research has taken place over the decades since the NHC's SLOSH surge model was developed leading to surge/water level/inundation models that can better resolve near shore and on shore features and that include the effects of processes including tides, surface waves, surge forerunners, coastally trapped waves, baroclinic currents (e.g., the Gulf Stream), and precipitation on coastal water levels that are not represented in SLOSH. Storm surge and water level metrics should independently measure errors due to the hurricane forecast and due to the surge model itself, to assess storm surge and water level forecast improvements with regard to both. Better risk communication requires, among other things, better understanding of all sources of uncertainty in forecast water levels. The HFIP plan ties storm surge forecast improvements to advances in hurricane modeling and to better storm surge output products, but there appear to be no explicit plans to systematically evaluate the accuracy of (and the need to improve) the storm surge modeling itself.

This is true despite the tremendous growth over the past decade of water level time series data from an expanded and hardened network of NOAA gauges, US Army Corps of Engineers gauges, the USGS rapid storm surge response program, state programs and other initiatives. Programs such as the US Integrated Ocean Observing System (IOOS) Coastal and Ocean Modeling Testbed (COMT) have provided rigorous evaluations of the National Hurricane Center's Sea, Land, and Overland Surges from the Hurricanes (NHC SLOSH) model versus other surge models for a few select storms. However, this has not continued and it is not clear whether it resulted in meaningful improvements in NHC's storm surge modeling capability. The same issue that applies to rapid intensification and rapid weakening apply here; measurements of sea level, coastal currents, surface waves and the wind distribution (e.g., wind stress) are pertinent to the robust evaluation of dynamical storm surge predictions and evaluations. Water hazards due to landfalling hurricanes can come from both storm surge and extreme rainfall. The occurrence of extreme rainfall appears to have increased in recent years, consistent with expectations of a warming climate. NOAA's CI-FLOW coastal and inland flooding observation and warning project aimed to predict the combined effects of storm surge, waves, and river inflow in North Carolina. The CI-FLOW project catalyzed partnerships among NOAA OAR, universities, and Sea Grant programs in 2000-2014.

Recommendation (3.1.1): HFIP should identify targeted stakeholders, and determine empirically what is required for information to be actionable for those stakeholders, as individual groups and as collectives, to set their forecast goals and storm surge metrics, including when and where a hurricane makes landfall and how high and how far its storm surge can reach inland. Needs that drive actionable lead times and products should be clarified and used to guide product development. In general, HFIP should continue to engage stakeholders in research to improve the usefulness of warning and watch products, and to improve the effectiveness of the guidance it offers for these products.

Recommendation (3.1.2): HFIP should focus on improvements to an integrated atmosphere-ocean-land model as hurricanes are approaching landfall, since coastal areas near landfall typically experience the greatest damage due to both wind and water. A program that systematically evaluates the performance of the NHC SLOSH model should be established, taking advantage of the large and growing number of water level time series that are available, to separate errors in water level predictions due to the surge model from those due to the hurricane model, and to set goals for improving surge model accuracy that are distinct from goals for improving hurricane model accuracy.

Recommendation (3.1.3): Goals and a strategy for advancing a more holistic coastal flood modeling capability, e.g., by modeling combined hydrologic and surge processes, should be established. Surge model forecast products should be developed that reflect uncertainty in the current storm rather than relying entirely on historical errors. HFIP should learn from and collaborate with past successful programs such as CI-FLOW and COMT to leverage this existing expertise to improve surge / water level / flood forecasts in coastal regions.

3.2 Enhancing Communication of Risk and Uncertainty for Hurricane Storm Surge

Findings: The risk communication research foci and strategies identified in the *HFIP Report* build on prior successful social and behavioral research on risk communication, especially with regard to storm surge threats. However, the potential social value of advances in weather forecasting capabilities has not been fully realized, due to insufficient research on how people perceive, interpret, and react to forecast and warning products for storm surges from hurricanes. NOAA-sponsored social and behavioral research, starting in 2010, engaged social scientists working with the operational forecast community to raise public awareness of the risk of storm surges from hurricanes. With limited resources, these research findings led to operational products, including the potential storm surge flooding map in 2016, and the storm surge watch/warning graphic in 2019.

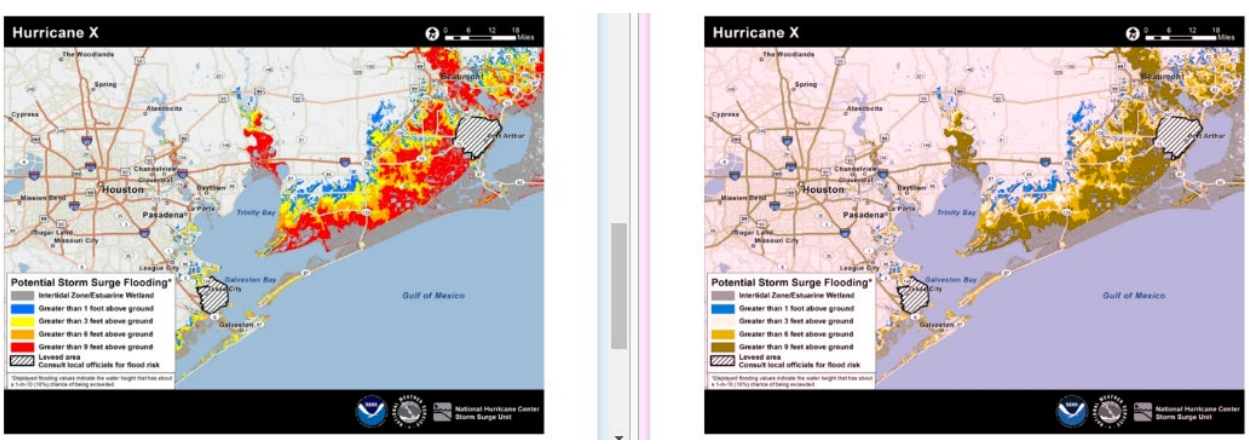

Figure 1: The same map displayed with different visual perceptions: on the left is a map of potential storm surge flooding from https://www.nhc.noaa.gov/surge/inundation/; the display on the right is what people with deuteranopia (red-green color blindness) see for the same map. People with deuteranopia will not be able to differentiate flooding "greater than 3 feet above ground" from the background (or will misinterpret that all the greater Houston area is subject to the potential of 3-ft flooding).

However, even for this successful line of research, gaps remain with regard to addressing the needs of specific users, such as emergency managers, and specific populations, such as those with disabilities. For example, the National Institutes of Health estimates have shown that 8-9% of the population, especially in Northern European descendants, has some form of color deficiency or colorblindness.[5] Color-blindness is an important consideration in map design, especially on web maps for the public, but may have been overlooked in the storm surge products. Having a clear strategy for incorporating up-to-date research[6] and tools[7] on the use of color in risk maps will be important going forward. There are three main types of color-blindness, and 99% of colorblind people have deuteranopia (red-green color vision defects). People with deuteranopia and tritanopia can, for example, miss "greater than 3 feet above ground" in the current potential storm surge flooding map (Figure 1). Moreover, people with achromatopsia (grayscale vision) can miss all risk categories.

Recommendation (3.2.1): Risk communication research should extend to other forecast and warning products for storm surges and hurricanes, such as rain, associated tornadoes, gusts, sustained winds, and inland flooding and to account for the potential impacts on and actions of both individuals and populations, including vulnerable populations.

Recommendation (3.2.2): Additional specific social and behavioral research is needed on factors influencing map interpretation and spatial cognition in the context of forecast and warning products, to guide appropriate design, understanding, and use of forecast products. Further research should quantify and communicate the inherent spatial and temporal uncertainty of surges from the NHC SLOSH model, and to assess its interpretability and usefulness by diverse groups.

Recommendation (3.2.3): Interdisciplinary research is needed to develop forecast products with improved location-specific risks relatable to responsive actions. Forecast products should provide the information needed to raise risk awareness when appropriate and to inform decision making in a timely manner. For example, NHC releases surge watch/warning graphics 48 hours before the possibility of life-threatening storm surge from a hurricane, but it provides no information on how fast the water can rise to the predicted height and the strength of the surge, as well as potential riverine flooding in space and time in relation to storm surges. Because most people perceive wind as the primary risk of hurricanes and remain less aware of

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[5] https://ghr.nlm.nih.gov/condition/color-vision-deficiency

[6] For example: Seipel, S., & Lim, N. J. (2017). Color map design for visualization in flood risk assessment. International Journal of Geographical Information Science, 31(11), 2286-2309.

[7] For example: http://www.colorbrewer.org/

the risk of flooding due to storm surge, it is vital to highlight the risk of storm surge, especially those associated with hurricanes of low categories.

Recommendation (3.2.4): Because people adjust their risk assessment and responses as a hazard progresses and as the forecast information changes – including storm surge forecasts – research is needed to understand how people adjust their assessments and responses as surge forecasts change, and as specific aspects of the forecast information itself change (e.g., locations threatened, surge levels).

3.3 Data Uncertainty and Considerations to Support R2O Enhancement

Findings: The strategy for R2O enhancement establishes initiatives to prioritize targeted research and joint efforts with the Joint Hurricane Testbed, Hydrometeorological Testbed, Joint Center for Satellite Data Assimilation, and Quantitative Observing System Analysis Project. The testbed approach is aligned with the NOAA transition funnel model. The strategy intends to link HFIP closely with R2O activities in the Forecasting A Continuum of Environmental Threats (FACETs) initiatives, though the report does not specify how. We currently discretize study of hazards and how people get information about them, perceive the risk from them, and respond to them. But in reality, when a hurricane threatens, people get information about winds, rain, surge, and sometimes tornadoes. Thus, research is needed to understand how people attend to, make sense of, assess risk from, and respond to this collection of hazards, and how the threats from them evolve. For some people and some tropical cyclones, attending to the risks of inland flooding from rainfall, or risks from high winds, may be more protective than focusing on surge.

The FACETs framework represents marked progress in weather forecasting by providing information on the continuum of environmental threats on a probabilistic grid of 1-km squared and 15-min updates for severe weather events. The FACETs Science and Strategic Implementation Plan (2014[8]) anticipates full implementation in 2023, but only some FACETs research has been operationalized. FACETs sets forward a new paradigm to develop a continuous stream of high-resolution probabilistic hazard information extending from days to within minutes of an event. The program has demonstrated some success for severe convective storms (tornadoes) and flash floods. If operationalized, FACETs could potentially revolutionize severe weather forecasting. Applying the FACETs framework could lead to marked improvements of hurricane forecast products.

Forecasts for storm surge are based on the SLOSH model with mosaicked digital elevation models (DEM) from various sources. The DEM data processing introduces uncertainty on elevations, and the uncertainty propagates in the modeling processes and hence the storm surge products. Further uncertainty in the storm surge products results from processes missing in the SLOSH model as identified in section 3.1. In R2O transitions, quantification and communication of the uncertainty in the products is essential for informed decision making. Not all users need to know details of uncertainty but recognizing who needs to know what is

[8] https://www.nssl.noaa.gov/projects/facets/FACETs%20SSIP_1.pdf

important to ensure effective forecast products, which calls for a clear identification of stakeholders and their information needs.

Recommendation (3.3): Hurricanes and storm surges operate at much greater spatial scales and involve more diverse physical processes than convective storms and flash foods. FACETs is essentially a framework that supports enhancing the parameter space of forecast information. Additional consideration of adopting the FACETs framework for storm-surge forecasts should address whether 1-km grids and 15-min updates are feasible and appropriate. Issues regarding data, uncertainty, communication, and feasibility need further attention. The planned R2O initiatives should include uncertainty information in the testbed experiments.

SECTION 4. Is the HFIP report responsive to the specific focus identified in (b)(3), "incorporating risk communication research to create more effective watch and warning products" ?

Summary Findings: HFIP notes the marked improvements from social/behavioral research on storm-surge flood maps and provides general plans to incorporate social/behavioral research on a suite of products, but the report lacks detail on how the advances will be achieved. Quantitative measures of success for risk communication research are lacking.

Summary Recommendation (4): Severe weather can evoke subsequent hazards; warning and watch products need to address risk from multiple threats. Developing a strategic plan for social and behavioral research with milestones and metrics should be a high priority to ensure forecasts and forecast products address diverse societal needs and impacts.

In this section, we focus on the two key needs for incorporating risk communication research, the first advocating for greater integration of social and behavioral science in risk communication activities, and second the need to define metrics that can measure success within the framework of a broader approach.

4.1 Elevating Social and Behavioral Sciences in Risk Communication Research

Findings: Little explicit reference is made in either the *HFIP Report* or the *HFIP Plan* to the extensive social and behavioral research NOAA and NSF have funded, some jointly. In general, the *HFIP Report* presents incomplete and inconsistently described goals for understanding and forecasting hurricane parameters and storm dynamics. For example, the *HFIP Report* focuses on rapid intensification, but ignores changes in storm size and addresses a storm's forward speed only indirectly (p 58 in the *HFIP Plan*), although these are critical for evacuation decisions.[9] The *HFIP Report* and *Plan* acknowledge that social and behavioral research led to marked improvements to storm surge watch/warning graphics. Expanding upon this success, HFIP aims to fully incorporate social and behavioral sciences into a wider suite of watch/warning products, information, and services for all hazards and to assess information needs for partners and stakeholders in communicating risk and uncertainty. The HFIP Plan recognizes the importance of the characteristics of information from physical science (e.g., risk, confidence, uncertainty), technological support (e.g. formats, interactivity), and messaging (e.g., graphics, interactive, apps). Perceptual, behavioral, and social factors and societal impacts merit additional HFIP attention. The HFIP plan notes examples of partners and stakeholders as emergency managers, broadcast media, and the general public (p. 71) without clear and consistent specifications of the targeted or prioritized users of warning and watch products. Interdisciplinary and social and behavioral science research is needed to identify and address information needs from all targeted users as individual groups and, as relevant, as a forecast and warning system.

NOAA's Office of Weather and Air Quality, NOAA's National Weather Service, and the Department of Transportation's Federal Highway Administration sponsored the National Academies of Sciences, Engineering, and Medicine (NASEM) study on *Integrating Social and Behavioral Sciences Within the Weather Enterprise.* The study's 2018 report identified three priority areas for social and behavioral research: (1) weather enterprise system-focused research, (2) risk assessments and responses, and factors influencing these processes, and (3) message design, delivery, interpretation, and use. HFIP's plan for social and behavioral research maps well with the three priorities and therefore stands ready as an excellent use case to implement the NASEM report.

Recommendation (4.1.1): While physical, technological, and messaging considerations are crucial to risk communication, research on how people assess and respond to risk as well as the factors influencing the processes as recommended in the NASEM report equally deserves HFIP's careful considerations. As hurricanes trigger multiple types of hazards and can take place simultaneously or consequently with other hazardous events (e.g., COVID-19 and heavy rainfall or landslides, respectively), research on multi-hazard products can further expand the success of storm-surge flood maps.

Recommendation (4.1.2): Additional social science should be conducted to assess the information needs of critical forecast users with regard to improved forecast products. As NWS moves towards a paradigm of Impact-based Decision-Support Services (IDSS), HFIP should recognize the needs of IDSS core partners—defined by NOAA as members of emergency management and water resources management communities, government partners, and the

[9] Lindell, M.K. (2020). Improving hazard map comprehension for protective action decision making. Frontiers in Computer Science. Doi: 10.3389/fcomp.2020.00097.

electronic media[10]— and pursue research with its academic and private sector partners on the characterization and communication of impacts, to address these needs.

4.2 Setting Metrics and Broadening Approaches to Enhancing Risk Communication

Findings: The *HFIP Plan* for 2019-2024 aspires to modernize all TC products by 2028 through completing a baseline understanding of partner and stakeholder needs by 2021 and transitioning 2-3 TC hazard guidance products per year to improve communication of the forecast risk by 2023. The plan's envisioned pathway in using social and behavioral sciences includes qualitative aims and the evaluation of current and future products in a naturalistic environment. However, the *HFIP Plan* suggests that these communication studies be conducted in NOAA's Hazardous Weather Testbed (HWT) and Operations Proving Ground; observations conducted at the HWT since 2017 suggest that HWT may fall short of a "natural environment" in several regards. Many other approaches—including but not limited to quasi-experimental field studies, and longitudinal operational product evaluations—could usefully complement simulations in evaluations of current and future products and operational paradigms.[11]

The only social and behavioral science objectives for risk communication in Table 2.4 (*HFIP Plan*) are for Goals 4.9, 4.10 and 4.11 (pp 75-77, *HFIP Plan*). No baselines for these are defined, and metrics/milestones are quantified primarily in terms of outputs, rather than outcomes (e.g., completion of a baseline assessment of NWS partner and user Tropical Cyclone information needs).

Research validity and generalizability are as or more challenging in social and behavioral sciences than in physical sciences. Risk communication research is complex yet sufficiently bounded and therefore is ripe for methodological research that deciphers scientific approaches to research delimitations, measurable objectives, replicable findings, and generalizable knowledge.

Recommendation (4.2): Like other research in weather forecasting, setting meaningful metrics for risk communication research is critical to tracking research progress. HFIP should identify measurable social and behavioral science research objectives and measure progress towards understanding current uses and needs, identify future TC info requirements, and evaluate the effectiveness of current and future risk communication products. These measures should be prioritized to indicate both the impacts of social science research as well as the performance of each metric for risk communication. HFIP should collaborate with NOAA's Social Science Committee and leverage the committee's 2016 report[12] on the best practices

[10] National Weather Service (NWS) Service Description Document: Impact-Based Decision Support Services for NWS Core Partners, April 2018, https://www.weather.gov/media/coo/IDSS_SDD_V1_0.pdf
[11] Demuth, J. L., Morss, R. E., Jankov, I., Alcott, T. I., Alexander, C. R., Nietfeld, D., ... & Benjamin, S. G. (2020). Recommendations for developing useful and usable convection-allowing model ensemble information for NWS forecasters. *Weather and Forecasting*, *35*(4), 1381-1406.
[12] https://www.performance.noaa.gov/noaa's-social-science-committee/

and research findings in risk communication and behavior to plan for a research strategy with performance metrics for social-behavioral science research that also allows new, relevant metrics to emerge. A promising first step for social and behavioral research would be to develop a meaningful first set of metrics, specifying who has defined them and for which users. A strategic plan for developing risk communication in true interdisciplinary collaborations between social and behavioral scientists and physical scientists should be developed to ensure forecasts address societal impacts and benefit HFIP.

SECTION 5. Expanding Partnerships and Collaboration to Accelerate Progress

> *Summary Findings:* The need for improved hurricane forecasts is urgent. Physical, social and behavioral sciences, as well as observation and modeling technology, are advancing across government, academic and industry sectors, while NOAA budgets are increasingly constrained. Broader coordination, internally across OAR, NWS and NOS, and externally across government, academic and industry sectors, will be required to support targeted research motivated by operational needs.
>
> *Summary Recommendation (5):* Increase internal coordination across OAR, NWS, and NOS and expand science and technology partnerships to achieve Weather Act goals.

Achieving progress on each of the above topics will require HFIP to enhance its partnerships and collaborations across NOAA, as well as with outside organizations and researchers, to help HFIP build capacity, advance research more rapidly, and move research into operations. The limitations on HFIP resources suggest that effective partnering strategies deserve even more attention than they have received to date. The National Academies report "Weather Services for the Nation: Becoming Second to None" (NASEM 2012) recommended that NOAA and the NWS leverage the entire weather enterprise. Building on this, a recent report noted that "to address expanding needs in a time of accelerating scientific and technological advancement, as well as uncertain and likely constrained budget resources, all available skills and competencies across the enterprise will have to be optimally coordinated and applied" (p 110, NASEM 2017).

In this section we emphasize that expanding partnerships is not a new or unrecognized path, that there are real barriers to overcome, and that active, productive and synergistic partnerships will be required to accomplish Weather Act goals. We highlight two specific partnerships that are critical for improving hurricane forecasts in a resource constrained environment, one internal with the National Ocean Service (NOS) and one external with the Navy. We conclude with comments that many pathways for collaborations with NOS, the Navy, other agencies, academics and industry already exist, and that it is time to use them.

5.1 Expanding Partnerships to Meet the Challenge

Findings: Increasing scope, level budgets, and balancing timeline extensions versus the urgent need for improvements certainly constitutes a challenge. Both the *HFIP Report* Executive Summary and the *Report's* Key Strategies highlight the recognized need for partnering. However, proposed new activities—including a Scientific Review Committee, the grants and contract program, and the envisioned outreach—generally fall short of what is needed to meet the urgent need. Many modeling and observational innovations are occurring outside of HFIP in the U.S. Navy, in NOAA's NOS, in academia, in other agencies, and in industry. For example, NASA and IBM have partnered to develop a machine learning model to assist in the prediction of hurricane intensity based on satellite data.[13] This is consistent with HFIP's desire to partner with other agencies and industry, and consistent with HFIP's 5th key challenge of better use of satellite observations to improve hurricane intensity forecasts. Transitioning a broader range of relevant innovations from research to operations must overcome barriers such as estimating cost-benefit ratios and economic impacts to justify the cost of the operational tail after transition.

While the HFIP strategy appears comprehensive, with a multipronged approach to broadening expertise and interactions, it is unclear the extent to which NOAA is able to take full advantage of the full range of relevant social and behavioral science expertise to guide and implement HFIP efforts. For example, on page 49 (*HFIP Plan*), it states: "Note: Federal agencies may not request or accept consensus opinions, advice or recommendations from the Science Advisory Committee. Instead, Science Advisory Committee members will be invited to provide their individual insight on the scientific direction and merits of HFIP activities." Outstanding ideas need substantial and broader support beyond NOAA and SAB to realize the vision.

Recommendation (5.1.1): The list of partners that OAR and NWS are actively engaging in HFIP should immediately be expanded to include NOS at the highest level. NOAA should also use existing mechanisms to include the Navy, the many academics already engaged in the OAR Cooperative Institutes, and the many government, academic and industry partners already collaborating through the NOS-led U.S. IOOS program. HFIP should engage broader communities of social and behavioral sciences to address current communication challenges.

Recommendation (5.1.2): HFIP should seek ways to leverage resources to support the planned strategy and seek opportunities to increase research interest from broader communities. HFIP should encourage projects to address the science challenges in the social and behavioral sciences, as well as the atmosphere and the ocean. Existing mechanisms for supporting collaborations on HFIP research—such as with the National Science Foundation to fund HFIP-focused social and behavioral science, and with the Navy and the OAR Cooperative Institutes to address atmospheric and oceanic research challenges—should be strengthened to achieve HFIP goals. Coordinated economic impact studies based on HFIP metrics should be conducted to help identify priorities and efficiencies, rather than requiring each individual scientist or technological innovation to conduct their own. This may not be possible at the

[13] https://www.nasa.gov/feature/jpl/a-machine-learning-assist-to-predicting-hurricane-intensity

current level of investment, but will be required to address the goals of the Weather Act on a time scale that matches the urgent need.

5.2. Expanding Collaborations with NOAA's National Ocean Service:

Findings: The Weather Act does not specifically require collaborations with NOAA's National Ocean Service (NOS) to improve hurricane forecasts in Section 104. However, Section 301 (a) (2) of The Weather Act (see Appendix 3) does provide a framework for collaborations. While Section 301 is directed at using ocean and coastal data available through the Integrated Ocean Observing System (IOOS) for improving weather forecasts and forecasting decision support systems in general, this is most certainly applicable to improved hurricane forecasting and warnings. NOS has also developed significant storm surge modeling experience within NOAA that is independent of NWS operations. The NOS Coastal and Ocean Modeling Testbed (COMT) has strong ties to the academic research community with significant hurricane forecasting and storm surge experience. NOS and their external academic partners are already collaborating with OAR and its academic partners through the use of autonomous marine systems, and with NWS for improvements to the ocean component of the coupled forecast models - additional collaboration could accelerate progress.

Recommendation (5.2.1): NOAA should proactively highlight the beneficial 3-way collaborations and synergies between OAR, NWS and NOS that already exist, and actively engage the broad and relevant expertise of NOS partners to strengthen or expand activities that can contribute to improved hurricane forecasts and warnings described in the *HFIP Report*. Two examples below already standout.

Recommendation (5.2.2): NOAA's Uncrewed Systems Strategy should leverage the many advantages of "distributed autonomy" already demonstrated by the diverse partners collaborating in the Hurricane Glider program that NOAA has coordinated since 2018. A rapid transition task team to define requirements for and expand observations from autonomous systems (e.g., profilers such as floats and gliders, or surface platforms such as drifters and unmanned vessels) should be formed that includes members of OAR, NWS, NOS and external (Navy, agency, academic, industry) partners. Technology development should enhance sensors on existing autonomous systems to collect additional gap filling data, fulfilling needs outlined in Section 2.

Recommendation (5.2.3): HFIP recognizes the importance of NOAA testbeds (Key Strategy E), and should include the NOS COMT as one of its collaborating testbeds. It should look for research opportunities that bring NOS, NWS (and NHC), and OAR together to better utilize storm surge modeling capabilities and expertise that already exists across the NOAA line offices and within the external community. External storm surge scientists already entrained through COMT should be included in interdisciplinary workshops intended to improve hazard forecast products.

5.3. Leveraging Collaborations with the U.S. Navy

Findings: US Hurricane forecasting activities leverage many of the best aspects of both NOAA and Navy capabilities in both science and operations to improve hurricane forecasts. These include: (a) The Navy Coupled Ocean Atmosphere Mesoscale Prediction System for Tropical Cyclones (COAMPS-TC) is one of the models envisioned in the future forecast ensembles that will be assembled in HAFS; (b) All ocean data assimilation for NOAA's operational hurricane forecasts is currently conducted by the Naval Oceanographic Command using the Navy's Global Ocean Forecast System (GOFS); (c) the Naval Research Lab has partnered with NOAA to transition the Navy Coupled Ocean Data Assimilation (NCODA) system to experimental use in NOAA's Real Time Ocean Forecast System (RTOFS); (d) The Naval Oceanographic Command also contributes about 10 Navy underwater gliders and shares the operating costs with NOAA each hurricane season; (e) The Navy Oceanographic Command releases selected operational Navy glider data to the IOOS Glider Data Assembly Center so that it can be shared with hurricane researchers as well as making it available to the operational centers through the Global Telecommunications System (GTS). On the research side, the Office of Naval Research (ONR) sponsored the CBLAST project that is cited by HFIP as a significant contributor to the early successes. ONR continues to sponsor typhoon and hurricane science field campaigns that include studies of rapid intensity change and cloud microphysics.

HFIP is faced with expanding scope, level funding, and an increasingly urgent need for results. Navy initiatives and field campaigns including those in the Pacific where typhoons are often more frequent and more severe provide an opportunity to gain and transfer knowledge to NOAA models and enhance already established collaborations. HFIP does provide an annual forum (TCORF) for interagency collaboration on hurricane forecasting.

Recommendation (5.3): NOAA should consider ways to expand the HFIP collaborations with the Navy beyond the TCORF forum to increase the rate of progress toward shared NOAA and Navy goals.

5.4 Building a Focused Collaborative Network

Findings: Working together across line offices, agencies and sectors to improve hurricane forecasts and warnings is a unifying goal that can bring together diverse groups and yield powerful results. Collaborative pathways already exist through a multitude of programs. Examples covering a broad range of activities include: the Weather Act required collaborations between OAR and NWS (Sec. 104) and between NWS, NOS and OAR (Sec. 301); the Commercial Engagement Through Ocean Technology Act of 2018 (CENOTE Act) requiring cordination between NOAA, Navy, industry and academics in unmanned maritime systems; a July 2020 NOAA workshop on expanding IOOS and OAR collaborations that included a focus on hurricanes; the Navy-NOAA collaboration MOU that includes shared use of autonomous assets; the OAR Cooperative Institutes (CIs) with academic researchers; the IOOS Regional Associations (RAs) with academic and industry partners; the data-sharing partnerships between NOAA and the offshore energy industry; and collaborations with NSF to jointly fund social and behavioral science research on communicating information.

*Recommendation (5.4)**:*** NOAA should take advantage of the already available partnership pathways to achieve more within HFIP in a reasonable time at a reasonable cost. Progress should include NOAA investments in (a) collaborative research bringing together the NOAA Research Labs and the distributed community in the OAR Cooperative Institutes, (b) the sustained operation of new distributed observing systems that leverage the NOAA Uncrewed Systems Strategy and the distributed implementation capabilities and local operational experience of the IOOS Regional Associations with their industry and academic partners, and (c) expanded ocean, social and behavioral science transition activities that follow the successful HFIP framework. Key gaps should be addressed by establishing focused centers of expertise, in physical locations or virtual, and through a visiting scientist/student program with both in-person and virtual visits.

SECTION 6. Review Summary

Through Title 1, Section 104, of the Weather Act, Congress has articulated the critical goal of improving hurricane forecasts and warnings to save lives, property and livelihoods. Even since the Weather Act enactment in 2017, there has been increasing recognition of the urgent need for action to support this goal.

NOAA leadership responded to the Congressional request with the *HFIP Report* that also draws from the *HFIP Plan* assembled by a team of 20 NOAA experts. The SAB EISWG used both documents, presentations by HFIP, and an external panel of six subject matter experts to assemble this review.

The review identifies and commends the vital role HFIP plays to rapidly transition promising research into operations to improve hurricane forecasts and warnings. The review also notes that the structural and financial limitations of HFIP must be addressed, and critical gaps filled, to more rapidly address the urgent goal of the Weather Act.

To achieve the goals of the Weather Act in a reasonable time, NOAA will need to continue to support HFIP plus: (1) invest in additional physical, social and behavioral science research, motivated and targeted by an expanded set of success metrics, (2) leverage scientific and technological advances enabled by other line offices, testbeds, agencies, organizations and industry, and (3) entrain a broader network of expert personnel external to NOAA for convergent research and workforce development. The many EISWG recommendations in this report often fall into one of these three categories.

APPENDIX 1.

EISWG Generated Overview of the NOAA *Report to Congress, Hurricane Forecast Improvement Program*

Title I, Section 104 of the Weather Act requires NOAA to maintain a project to improve hurricane forecasting. The Weather Act's Goal is to develop and extend accurate hurricane forecasts and warnings in order to reduce loss of life, injury, and damage to the economy. To accomplish this Goal, the Weather Act defines three Focus areas:

1) Improving the prediction of rapid intensification and track of hurricanes.
2) Improving the forecasting and communication of storm surges from hurricanes.
3) Incorporating risk communication research to create more effective watch and warning products.

In NOAA's *Report to Congress, Hurricane Forecast Improvement Program* (HFIP), the Executive Summary states that the Office of Oceanic and Atmospheric Research (OAR) and the National Weather Service (NWS) will continue to address existing science and research-to-operations challenges by:

1) Improving regional and global models
2) Transitioning promising innovations from research to operations
3) Partnering with academics, America's Weather Industry, and the emergency response community.

The HFIP Report has identified five challenges to achieving the Weather Act goal:

1) Reduce HWRF guidance errors for rapid intensification
2) Reduce global modeling guidance errors to extend forecast time
3) Improve utilization of high resolution ensembles for initialization and products.
4) Better utilization of satellite observations in clouds
5) Better utilization of all observation platforms (satellite, ocean, aircraft) for intensity.

Building on its original track and intensity metrics, HFIP has identified 4 new metrics for success:

1) Reduce numerical forecast guidance errors, including RI, by 50% from 2017 baseline.
2) Produce 7-day forecast guidance similar to the 2017 5-day guidance.
3) Improve guidance on pre-formation disturbances, including genesis timing, and track and intensity forecasts by 20% from 2017.
4) Improve hazard guidance and risk communication, based on social and behavioral science … for actionable lead times for storm surge and all other threats.

NOAA's HFIP plan proposes six Key Strategies to achieve the overall Goal, summarized here as:

A) Advance an operational Hurricane Analysis and Forecast System (HAFS).

B) Improve probabilistic guidance following the Forecasting a Continuum of Environmental Threats (FACETs).
C) Enhance communication of risk and uncertainty.
D) Support dedicated High Performance Computing (HPC) allocations.
E) Enhance R2O, including utilizing NOAA testbeds.
F) Broaden expertise and expand interactions.

Each Key Strategy contains 3-5 Priorities and 4-5 Objectives.

HFIP annual core funding for FY19 was $12.9M (Source: *HFIP Report* Executive Summary)

1. Within OAR, Laboratories and Cooperative Institutes received $5.9M, and the Weather Research Program received $0.5M.
2. Within NWS, S&T Integration received $4.5M, and Central Processing received $2.0M.

Maximum core funding for HFIP was $27.14M in FY09. Core funding dropped to $14.3M in FY15 and dropped again to $12.7M in FY17. Congressional Hurricane Supplementals at times provide critical additional support ($10M in FY13, $3.6M in FY14, $9M in FY18, and $2.2M in FY19). Maximum total funding including supplementals was $32.8M in FY13 (Source: HFIP Presentations).

APPENDIX 2.

Subject Matter Experts Consulted for this Report

Julie L. Demuth, Ph.D. Project Scientist II – Mesoscale and Microscale Meteorology Laboratory, National Center for Atmospheric Research (EISWG member as of August 2020)

James D. Doyle, Ph.D., Senior Scientist ST, Marine Meteorology Division, U.S. Naval Research Laboratory

Kerry A. Emanuel, Ph.D., Professor of Atmospheric Science, Massachusetts Institute of Technology

Michael Lindell, Ph.D., Emeritus Professor, Texas A&M University; Affiliate Professor, University of Washington Department of Urban Design and Planning; Affiliate Professor, Boise State University Department of Geosciences; Affiliate Professor, Oregon State University School of Civil and Construction Engineering

Rick Luettich, Ph.D., Professor and Director, Institute of Marine Sciences, College of Arts and Sciences, The University of North Carolina at Chapel Hill

Lynn K. (Nick) Shay, Ph.D., Associate Dean of Research and Professor, Department of Ocean Sciences, Meteorology and Physical Oceanography Program, Upper Ocean Dynamics Laboratory/WERA Operations, Rosenstiel School of Marine and Atmospheric Science, University of Miami

APPENDIX 3.

Weather Act Title III, Sec. 301(a)(2)

PUBLIC LAW 115–25—APR. 18, 2017
Title III / Sec. 301(a)(2)

INTEGRATION OF OCEAN AND COASTAL DATA FROM THE INTEGRATED OCEAN OBSERVING SYSTEM.—In National Weather Service Regions where the Director of the National Weather Service determines that ocean and coastal data would improve forecasts, the Director, in consultation with the Assistant Administrator for Oceanic and Atmospheric Research and the Assistant Administrator of the National Ocean Service, shall—

(A) integrate additional coastal and ocean observations, and other data and research, from the Integrated Ocean Observing System (IOOS) into regional weather forecasts **to improve weather forecasts and forecasting decision support systems**; and
(B) support the development of real-time data sharing products and forecast products in collaboration with the regional associations of such system, including contributions from the private sector, academia, and research institutions to **ensure timely and accurate use of ocean and coastal data in regional forecasts**.
(C) support increasing use of autonomous, mobile surface, sub-surface, and submarine vehicle ocean and fresh water sensor systems and the infrastructure necessary to **share and analyze these data in real-time and feed them into predictive early warning systems.** (C was added with NIDIS reauth. Act S2200 in 115th Cong.)