National Oceanic and Atmospheric Administration (NOAA)
Response to the Science Advisory Board (SAB) Environmental Information Services Working Group (EISWG) report on the Hurricane Forecast Improvement Program (HFIP)
November 22, 2021

Hurricane Forecast Improvement Program Five-Year Plan: 2019-2024

The National Oceanic and Atmospheric Administration (NOAA) Hurricane Forecast Improvement Program (HFIP) Five-Year Plan details the specific research, development, and technology-transfer activities necessary to tackle HFIP's science and Research to Operations (R2O) challenges to address three primary focus areas as stated in Section 104 of the Weather Research and Forecasting Innovation Act of 2017:

1. improving the prediction of RI and track of Tropical Cyclones (TCs);
2. improving the forecast and communication of surges from TCs; and
3. incorporating risk communication research to create more effective watch and warning Products.

To address all three areas, the plan identifies a set of specific goals, and key strategies to achieve those goals and metrics to measure progress toward those goals are described in great detail. The final plan was first released in 2018 and updated in 2019.

The Review

The NOAA Science Advisory Board's (SAB) Environmental Information Services Working Group (EISWG) reviewed the above HFIP Five-Year Plan and submitted a report concerning the Hurricane Forecast Improvement Program on October 13, 2020. The report was approved by SAB at its October 28, 2020 virtual meeting and was transmitted to NOAA on November 5, 2020. The report provided five summary recommendations and specific recommendations for each summary recommendation to the NOAA SAB. NOAA's response to that report follows.

Response to High-Level Recommendations

Recommendation# 1

Overall Project Plan: To address The Weather Act Title I, Sec. 104 (c), the expanded scope must be mapped to necessary resources and timelines.

Response: NOAA base support (~$14M/year for FY19-FY22) and short-term supplemental projects under the Bipartisan Budget Act of 2018 (P.L.115-123) and the Additional Supplemental Appropriations for the Disaster Relief Act of 2019 (P.L.116-20) were used to accelerate four key strategies outlined in the 2019 HFIP Strategic Plan:

1. Development of the Hurricane Analysis and Forecast System (HAFS) to improve forecast guidance on track and intensity, including rapid intensity change;

2. Social Behavioral and Economic Science (SBES) Research to improve communication of risk;
3. Increased Research and Development High Performance Computing (RDHPC); and
4. Provide grants to broaden expertise and expand interaction with the external community.

The budget reduction associated with the HFIP since FY15 slowed the rate of progress towards the 10-year HFIP goals by restricting the capacity to test and evaluate new research and delaying the transition of potential new analysis and forecast applications into operations. Reduced funding levels also hindered engagement with the academic community that dramatically slowed model improvements. The required annual budget for HFIP to address expanded scope is ~$22M. Disaster Supplemental resources from FY18 and FY19 provided one-time support of ~$20M over 3 years in hurricane focused research, of which ~60% went to Federal grants, and ~$25M for RDHPC. The follow-on FY22 Disaster Supplemental resources will provide $15M over 2 years to address some gaps. Hurricane research will have access to about one third of the $50M RDHPC resources available from FY22 Disaster Supplemental as well.

Recommendation# 2

Rapid Intensification (RI) and Track: 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.

Response: HAFS development is leveraging the advancements in the Unified Forecast System (UFS) and Joint Effort for Data Assimilation (JEDI) systems through Disaster Supplemental, UFS R2O, Earth Prediction Innovation Center (EPIC), and Federal grants, which also serve as touchpoints with broader community efforts.

HFIP developed collaborations with Office of Naval Research (ONR) on Tropical Cyclone Rapid Intensification (TCRI) initiative (2020-22) and OAR/Global Ocean Monitoring and Observing (GOMO) and NOS/ Integrated Ocean Observing System (IOOS) on use of ocean observations to improve RI guidance (2021-2022).

Recommendation# 3

Forecast and Communication of Storm Surges: Communicating storm-surge risk should be prioritized, 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.

Response: Owing to the budget reduction, storm surge research and development is now largely being supported by the Consumer Option for an Alternative System to Allocate Losses (COASTAL) Act and UFS. Any budget reduction to the COASTAL Act Program budget will impact work leveraged to the HFIP Program. Current storm surge modeling activities are now coordinated under UFS through the Marine and Land Working Groups.

The Disaster supplemental and COASTAL Act supported extension of storm surge forecast lead times to 3 days with the same skill as 2-day and the OCONUS development of storm surge guidance for Puerto Rico, U.S. Virgin Islands, Hawaii, and Guam.

UFS is setting up a testbed to compare community coupled atmosphere- wave-ocean-hydrology models to assess their relative performance.

Recommendation# 4

Risk Communication Research for Watch/Warning Products: Watch and warning products need to address risk from multiple threats. Developing a strategic plan for SBES research with milestones and metrics should be a high priority to ensure forecasts and forecast products address diverse societal needs and impacts.

Response: HFIP Strategic Plan Appendix A.2.4 outlines goals and metrics for SBES research to improve hazard guidance and communications of risk for all hazards. Due to budget reduction, HFIP is not able to support social science research at the levels planned or desired. Disaster Supplementals provided ~$3M over 3 years for this research (FY19-22) to support 6 projects. Additionally, the Office of Oceanic and Atmospheric Research (OAR) Weather Program Office (WPO) and National Weather Service (NWS) Science Technology and Integration (OSTI) budget portfolios are providing ~$1.5M over 2 years (FY20-21) to support an additional 5 SBES projects for research, testing, and evaluation of hurricane hazard services.

Recommendation# 5

Expanding Partnerships and Collaboration: Increase internal coordination across OAR, NWS and National Ocean Service (NOS), and expand science and technology partnerships to achieve Weather Act goals.

Response: Enhanced collaboration across OAR, NWS, and NOS is occurring through the UFS R2O project, NOAA Modeling Board, Disaster Supplemental, Storm Surge, GOMO's Extreme Events Ocean Observing Task Team (EEOOTT), and COASTAL Act.

For overall hurricane research to operation enhancement, we integrate more with NOAA testbeds such as the Joint Hurricane Testbed (JHT), Developmental Testbed Center (DTC), Joint Center for Satellite Data Assimilation (JCSDA), and Hazardous Weather Testbed (HWT).

Response to Specific Recommendations

Response Summary Table

Specific Recommendations	**NOAA Response**

HFIP 1. Overall project plan: To address The Weather Act Title I, Sec. 104 (c), the expanded scope must be mapped to necessary resources and timelines.	
1.1 Historical Goals: 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.	NOAA made significant progress toward achieving HFIP goals in the first 5-6 years of the program, and this resulted in a 20% reduction in errors from numerical guidance for both storm track and intensity. Intensity improvements were driven largely by improvements in the HWRF model's resolution, physics, and data assimilation. As a result, the The Hurricane Weather Research and Forecasting (HWRF) model has consistently been the best intensity model in the Atlantic basin since 2015. Starting in FY 2015, NOAA dedicated fewer resources to HFIP due to competing budget priorities. This budget reduction slowed the rate of progress towards the 10-year HFIP goals by restricting the capacity to test and evaluate new research and delaying the transition of potential new analysis and forecast applications into operations. Reduced funding levels also hindered engagement with the academic community that dramatically slowed model improvements.
1.2 Scope, Resources and Timelines: 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.	HFIP, Disaster Supplemental resources, the UFS R2O Project and Atlantic Oceanographic and Meteorological Laboratory (AOML) funding targets high-priority components of the HFIP strategic plan. Full execution of the plan within a reasonable timeline will require significant new resources (~$22M per year).
1.3 Developing a Convergent Interdisciplinary and Integrated Approach: 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	HFIP is a joint effort between OAR and NWS, and the team have been actively engaging with other NOAA line offices, including NOS and the National Environmental Satellite, Data, and Information Service (NESDIS), and external community through HFIP, FY18 and FY19 Disaster Supplemental, UFS R2O, and AOML funding to address gaps. HFIP also provides Federal grant funding opportunities every two years to help the transition of high readiness level research from the external community to operations.

<table>
<tr><td>community, are required to support targeted short-term to long-term research and technology development motivated by operational needs.</td><td></td></tr>
<tr><td colspan="2">HFIP 2. Rapid Intensification and Track: 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.</td></tr>
<tr><td>2.1 Addressing the Challenges of Forecasting Intensity Change and Track: 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.</td><td>The HFIP 5-Year Strategic Plan clearly articulates the model development priorities with a focus on high-resolution ocean/wave/surge coupled system with advanced data assimilation capabilities, which are geared towards addressing the forecast improvements to genesis, track, intensity change, structure, precipitation, and landfall impacts.

HFIP also fosters enhanced collaborations with international TC forecast agencies and research institutes to advance the model development, operational applications, research, testing, and evaluation of NOAA hurricane modeling systems in various global basins, e.g., Indian and Western Pacific Ocean basins. Feedback on model performance from these international partners was valuable in improving NOAA's operational hurricane forecast models for global TC forecasts. In addition, each year, the National Hurricane Center (NHC) and the Joint Typhoon Warning Center (JTWC) identify challenging storms, and operational modeling centers in the US and abroad present their perspectives on the performance of operational models at the HFIP annual workshop. These efforts led to the formation of the "Difficult TC Cases Working Group" consisting of model developers and researchers from NOAA laboratories, operational centers, academia, and NHC forecasters. This group collectively designs and executes modeling studies to identify critical deficiencies in TC modeling, data assimilation, and product generation.</td></tr>
<tr><td>2.2 Expanding Probabilistic Forecasts: NOAA should provide a stronger plan on</td><td>In "HFIP 5-Year Strategic Plan", NOAA has laid out a detailed plan to improve and extend the forecast</td></tr>
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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.	guidance on TC pre-formation, track and intensity forecasts up to 7-days from the deterministic model, and single- and multi-model ensembles for probabilistic forecasts. NOAA is interested in conducting suggested studies. Increased resources are needed to implement thorough investigation and to draw statistically meaningful conclusions. NOAA started by combining NOAA's own real-time TC ensemble with Navy's operational COAMPS-TC ensemble to create a national multi-model ensemble. The experiment provides additional uncertainty associated with deterministic TC track and intensity forecast guidance, as well as multi-model ensemble mean forecasts.
<u>2.3 Advancing Ocean Model Data Assimilation:</u> 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	With support from Disaster Supplemental projects, a prototype Marine JEDI with 3DVar methodology for ocean data assimilation for Modular Ocean Model - 6 (MOM6) has been achieved. Further advancements with a hybrid data assimilation approach is a near-future focus. Further support is required for joint AOML-EMC-PSL efforts to explore and develop JEDI based coupled DA for regional HAFS. OSEs and OSSEs efforts are currently planned in collaboration with EMC and AOML. However, support is needed for: 1. development of Forecast Sensitivity Observation Impact (FSOI)/Ensemble

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.	Forecast Sensitivity Observation Impact (EFSOI) tools for hybrid ocean DA; 2. ia nature run for conducting OSSE experiments, preferably in a coupled atmosphere-ocean configuration at high resolution covering multiple years; and 3. harnessing efforts for all relevant ocean observations from both in situ and remotely sensed platforms for Hurricane predictions. Significant computational resources are essential to accomplish the above at operational and soon-to-be operational model grid resolutions.
<u>2.4 Improving Coupled Atmosphere-Ocean Process Parameterizations:</u> 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	Recent hurricane-ocean-wave coupling studies document the importance of inclusion of non-linear interactions among the coupled component models for hurricane forecasts. Better refinement of numerical representations of fluxes across the air-sea interface and better understanding of the underlying processes are necessary through improved observations, data assimilation and coupling science. Progress is being made in ocean and coupled (atmosphere-ocean) data assimilation via projects supported by Disaster Supplemental and others like OAR/GOMO's IMPACT. Such efforts are focused on: 1. using sustained and target measurements with sampling strategy to have concurrent/coincident atmospheric-ocean observations; 2. incorporating impacts of precipitation and river freshwater discharge in the coupled ocean model component; 3. ocean and coupled data assimilation methods within the JEDI framework; 4. exploring use of regional MOM6 domains for high resolution data assimilation methods using JEDI; 5. ocean and wave coupling for the regional and global with nest configurations of HAFS

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.	6. Experiments on both two-way (ocean-atm) and three-way (ocean-atm-waves) coupling with HAFS; and 7. Study the role of sea spray in the air-sea interaction processes - research including both field and lab work to support numerical simulations.
2.5 Expanded Metrics: 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.	HFIP 5-Year Strategic Plan identified specific goals JEDI and metrics to quantitatively measure progress towards achieving those goals. Comprehensive key verification and validation metrics for UFS applications, including the Hurricane application, were identified through the NOAA sponsored 3-day 2021 Developmental Testbed Center (DTC) UFS Evaluation Metrics Workshop. The workshop produced community vetted metrics with participants from DOD, DOE, International, NOAA,National Aeronautics and Space Administration (NASA), National Center for Atmospheric Research (NCAR), private sector, and Universities. Final metrics lists have been shared with all UFS applications and working groups. The Disaster Supplemental project is also supporting the development of new metrics and diagnostics beyond the track and intensity as part of the HAFS development. See the latest HFIP Annual Report for a summary of some of these new diagnostics.
2.6 Conducting the Science Campaigns: 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	In 2005 the Intensity Forecast Experiment (IFEX) was developed as a partnership between operations (NWS, Aircraft Operation Center (AOC)) and research (AOML/HRD, NESDIS) to make the best use of NOAA's aircraft platforms to observe TCs to provide situation awareness, model initialization, test and evaluate new observing technologies, and better characterize the observed

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.	TC evolution. In 2009 IFEX became the observational program for HFIP to ensure that all the observations needed to improve and initialize the hurricane models such as Geophysical Fluid Dynamics Laboratory (GFDL), HWRF, and HMON. Over the 16 years the IFEX collaboration has stood the test of time and became the modus operandi to collect observations to support TC operational and research interests, flying 454 P-3 missions into 102 TCs. The success of IFEX and HFIP enabled NOAA to partner with other Agencies (ONR, NASA, and NSF) to increase the capacity to collect observations in TCs to accelerate model development, evaluation, and analysis to initialize the hurricane forecast models. IN 2021 IFEX is partnering with ONR's TCRI and NASA's Convective Properties Experiment (CPEX), and in 2022 with GOMO's EEOOTT. As HFIP increases support for research into TC hazards at landfall, IFEX is evolving into the [Advancing Prediction of Hurricane Experiment (APHEX)]() with closer ties to the partners supporting the observation program for the COASTAL Act.
<u>2.7 Continue Building the Model Test Environment - HAFS:</u> 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	HFIP is gone of the earliest programs in NOAA that laid the foundation for strong community involvement. There are about 800-1000 HWRF users around the world at this time. The community code releases were facilitated by NCAR/DTC in 2012. In addition, under HFIP, community interactions were established by sharing HPC resources with universities, and by creating funding opportunities. A summary of progress from these NOAA funded efforts is reported in our yearly reports. HFIP continues to coordinate the developments of HAFS. EPIC should support the HAFS public release when the first operational configuration is released. HAFS will replace operational HWRF and HMON. In parallel, HAFS is being developed as a coupled system with oceans and wave models where the coupling infrastructure developments are leveraged with UFS tools and utilities including the National Unified Operational Prediction Capability (NUOPC), Community Mediator for Earth Prediction Systems (CMEPS) and Community Data Models for Earth Predictive Systems (CDEPS). These tools are also being used to provide freshwater-saltwater coupling in other projects (like COASTAL Act) which will

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.	facilitate future advancements within HAFS.
2.8 Building the Distributed Data Archive: 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.	Flight level data and Doppler data from NOAA P-3s are available at AOML. The model analysis and forecast data are available at NCEP via NOAA Operational Model Archive and Distribution System (NOMADS) server. However, a FAIR distributed database for enabling all hurricane-relevant datasets is not available at this time and is a goal for the future. Plans are to include model analysis and forecasts data into the NOAA Big Data Program initiative so that the data is readily available on the cloud for easy access and research.
2.9 Forming the Diverse Research Teams: 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.	HAFS is being developed as the next generation Hurricane forecast system as a Unified Forecast System based application. This allows for infrastructure and science working groups of the broader UFS community to engage in technical and scientific advancements of Hurricane research. It also helps build cross-collaborations with other ongoing projects -- namely JCSDA's JEDI, OAR funded Ocean IMPACTS; IOOS funded COMT, COASTAL Act and National Academy of Sciences, Engineering and Medicine (NAS) Gulf Research Program. The above projects are leveraging developments in the following areas which broaden participation in Weather Act goals: 1. Regional MOM6 for hurricane application; 2. Science and infrastructure for actively coupling FV3-MOM6-WW3; 3. Marine-JEDI to accelerate ocean data assimilation developments; 4. Ocean observations in a combination of

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<tr><td></td><td>sustained and target sampling from the turbulent scales to meso scales;
5. The air-sea modeling advancement, including sea spray;
6. Advancement of the ocean modeling by including in-situ river discharge and precipitation, to better simulate the freshwater barrier layer.</td></tr>
<tr><td colspan="2"><u>HFIP 3. Forecast and Communication of Storm Surges</u>: Communicating storm-surge risk should be prioritized, 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.</td></tr>
<tr><td><u>3.1 Improved Models for Hurricanes Approaching Landfall and Storm Surge:</u>

<u>3.1.1:</u> 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.

<u>3.1.2:</u> 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</td><td>3.1.1: These stakeholders have been identified by the COASTAL Act program and the UFS Marine and Land Working Groups. Regarding the former, the targeted stakeholder is the Federal Emergency Management Agency (FEMA), and a fixed set of actionable hindcast model outputs have been identified, including hydrographs, and significant wave height and precipitation time series over the entire inundated region where indeterminate property losses have occurred. A specific metric has been identified, namely a 90% accuracy level of the full time series (not just the high water mark). For the weather-scale forecast mission, the UFS Coastal has identified stakeholders ranging from NWS National Centers and Weather Forecast Offices to Federal and State Emergency Managers, and academic partners. The needs of these groups are being used to guide the design of a future coupled UFS atmosphere-wave-storm surge model. This UFS model will be open source, and made available to our community partners in research to assist in the improvement of this model.

3.1.2: We agree with this recommendation. Intercomparison of various coupled wave and surge models, including the operational SLOSH model, was conducted at IOOS COMT and the <u>recommendations on operational surge models</u> were submitted to NHC. Within UFS Coastal, a</td></tr>
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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. 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.	testbed is being prepared in which a number of community coupled atmosphere-wave-ocean-hydrology models will be intercompared to further assess their relative performance. The NHC SLOSH model will be included in this evaluation along with newer and more advanced models. If resources permit, we will take up the COMT recommendation to use this testbed to quantify the intrinsic error of the coupled surge models relative to the error due to the hurricane model forcing. 3.1.3 Within the UFS Marine and Land Working Groups, a white paper is currently being drawn up in collaboration with the academic community to establish goals and a strategy for a future coupled coastal flood modeling capability for Total Water Level prediction. Leveraging the UFS infrastructure, the foundation of this future coupled system will be community models and the ESMF/NUOPC coupling framework. This writing team includes the COMT Program Manager in order to incorporate the knowledge base from its successful coupled model testbeds into our strategy.
3.2 Enhancing Communication of Risk and Uncertainty for Hurricane Storm Surge: 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. 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	3.2.1. We agree with this recommendation. Much of the existing efforts are currently being funded by the WPO Social Science Program, WPO Joint Technology Transfer Initiative Program, or the 2018 NWS/WPO Social Science Disaster Supplemental projects. As an example, one of the 2018 NWS/WPO Social Science Disaster Supplemental currently funded social science projects is looking across hurricane hazards including storm surge, rain, inland flooding, tornadoes, and winds. 3.2.2. As an example, one of the 2018 NWS/WPO Social Science Disaster Supplemental currently funded social science projects is looking at map perceptions as it relates to numeracy and will provide recommendations for some improvements. 3.2.3 As an example, one of the WPO Social Science Program currently funded social science Disaster Supplemental projects will collectively

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. 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 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. 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	provide research guided recommendations for how we could enhance product design (both visual and/or verbal). While it won't cover every product and service in detail, it provides a start. 3.2.4. As an example, one of the WPO Social Science Program currently funded social science hurricane projects is looking at how risk perceptions evolve over the course of a hurricane. We continue to proactively seek out opportunities to leverage the results of these projects through internal NOAA support opportunities and future Disaster Supplementals.

change (e.g., locations threatened, surge levels).	
<u>3.3 Data Uncertainty and Considerations to Support R2O Enhancement:</u> 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.	3.3 Currently, NHC is a leader in incorporating both social and physical sciences into their uncertainty product development as well as the adoption of new warning dissemination systems. For example, NHC recently led the adoption of a fully collaborated gridded warning for storm surge which dramatically increased the spatial and temporal resolution from zone-based approaches to 2.5 km gridded approaches. Additional improvements require significant investments in NWS dissemination, the adoption of polygon-based warning systems (aka Hazard Services) and overall improvements in Advanced Weather Interactive Processing System (AWIPS) architecture and/or cloud-based approaches. In partnership with OAR, efforts are underway to expand the Joint Hurricane Testbed capabilities to enable the testing and evaluation of the aforementioned service improvements.
<u>HFIP 4. Risk Communication Research for Watch/Warning Products</u>: Watch and warning 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.	
<u>4.1 Elevating Social and Behavioral Sciences in Risk Communication Research:</u> <u>4.1.1:</u> 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	4.1.1. We agree with this recommendation. Much of the existing efforts are currently being funded by the WPO Social Science Program, WPO JTTI Program, or the 2018 NWS/WPO Social Science Disaster Supplemental projects. As examples, there are projects funded by both the Disaster Supplemental as well as from WPO funding competitions to support tropical projects that look across multiple hazards, including one that assesses COVID-19 as well. 4.1.2 As examples, there are projects funded by both the Disaster Supplemental as well as from WPO funding competitions to support tropical projects that include NWS core partners and their needs as a primary focus. We continue to proactively seek out opportunities to leverage the

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. 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 electronic media and pursue research with its academic and private sector partners on the characterization and communication of impacts, to address these needs.	results of these projects through internal NOAA support opportunities and future Disaster Supplementals.
4.2 Setting Metrics and Broadening Approaches to Enhancing Risk Communication: 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	We agree with you and are working toward the development of a meaningful set of metrics. As an example, in September 2019, WPO hosted a weather-focused, Social Science Research to Operations Workshop where, among many topics, we focused on the development of meaningful metrics. Currently, there are many initiatives underway within NWS, WPO, and NOAA-at-large (including with the NOAA Social Science Committee), to enhance social science organizational infrastructure to support these efforts. We are actively looking for resources to further our baseline and longitudinal data collection efforts to support information requirement development, measuring progress, as well as advancing risk communication in the agency.

and leverage the committee's 2016 report on the best practices 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.	
HFIP 5. Expanding Partnerships and Collaboration: Increase internal coordination across OAR, NWS and NOS, and expand science and technology partnerships to achieve Weather Act goals.	
5.1 Expanding Partnerships to Meet the Challenge: 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. 5.1.2: HFIP should seek ways to leverage resources to support the	5.1.1 Partnership among OAR, NWS, NOS and NESDIS is strong, particularly through the FY18 and FY19 Disaster Supplemental projects which are coordinated across Line Offices. Further coordination is provided at the Assistant Administrator Level of each Line Office through NOAA's Hurricane Executive Oversight Board (HEOB) and the Weather Water Climate Board (WWCB). The FY18 and FY19 Disaster Supplemental resources also support SBES research to improve hurricane risk communication strategies. NOAA provides opportunities to the academic community, particularly through the OAR-WPO Joint Hurricane Testbed competition. NOAA also is coordinating with the Navy on hurricane observations and atmospheric and oceanic modeling. The UFS R2O Project includes NOAA EMC, OAR Labs, Cooperative Institutes, UCAR and Universities. This project includes hurricane

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 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.	research and may be used more extensively for future hurricane forecast development. 5.1.2: Early on HFIP collaborated with NSF on supporting social science research related to hurricanes. But, owing to budget cuts, HFIP has not been able to support social science research at the levels planned or desired. Much of the existing efforts are currently being funded by the WPO Social Science Program, WPO JTTI Program, or the 2018 NWS/WPO Social Science Disaster Supplemental projects. We will continue to proactively seek out opportunities to leverage their results and/or engage programmatically to communicate HFIP needs Regarding the social sciences, there are past and ongoing WPO partnerships with NSF to leverage NSF's theory building projects and bridge them to applications. There is also a current IAA with NSF to the Natural Hazards Center to support "Weather Ready Research" quick response research tied to the priorities in the Weather Act. This partnership has diversified the disciplinary backgrounds attracted to NOAA's social science challenges in addition to advancing NOAA's social science efforts related to data publication through the Hazards Center's collaborative NSF work on Designsafe-CI. HFIP has not been able to support these efforts. We will, however, continue to leverage partnerships with NSF to meet HFIP needs.
5.2 Expanding Collaborations with NOAA's National Ocean Service 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. 5.2.2: NOAA's Uncrewed Systems Strategy should leverage the many	5.2.1 We share your vision. There are active, ongoing collaborations between OAR, NWS, NOS, and ONR through the GOMO/OAR's Extreme Events-Ocean Observations Task Team (EEOOTT). This group consists of NOAA (OAR, NWS, NOS) and non-NOAA (e.g., academic institutions) subject matter experts responsible for observations, forecasts, research modeling, funding, and logistical support. The EEOOTT has also convened working groups of subject matter experts to address multiple facets of improving hurricane intensity forecasts, including modeling and data assimilation, integrated ocean-atmosphere observations, and resourcing. 5.2.2 While a rapid transition task team has not been formed to define requirements, the

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. 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.	EEOOTT's [described above in 5.2.1] Integrated Observations Working Group is working to coordinate in situ ocean and atmosphere observing platforms (e.g., gliders, drifters, Saildrones, Argo and ALAMO floats, sUAS, etc.) to improve hurricane intensity forecasts. The group is leveraging existing observations and seeking opportunities for co-deployments and simultaneous observations of the ocean and atmosphere throughout the Atlantic hurricane season(s). They are also exploring the use of uncertainty from model results to help design better ocean observing systems. Also, studies from AOML have demonstrated that Ocean gliders have proven to show a positive impact on hurricane predictions and the results were published. 5.2.3: This is an excellent suggestion given the focus on better communicating the risk of storm surge and all hazards posed by hurricane landfall called out in Section 104 of the Weather Act and the HFIP Strategic Plan. The existing storm surge modeling setup is based on the COMT recommendations. For overall hurricane research to operation enhancement, we integrate more with NOAA testbeds such as the Joint Hurricane Testbed (JHT), Developmental Testbed Center (DTC), Joint Center for Satellite Data Assimilation (JCSDA), and Hazardous Weather Testbed (HWT).
5.3 Leveraging Collaborations with the U.S. Navy: 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.	THis is an excellent suggestion. The US Navy has recently begun operational use of ensembles from COAMPS-TC. NOAA/HFIP should revive and expand our earlier partnership with the US Navy to explore use of multi-model ensembles for generation of probabilistic guidance for the forecasters. Efforts on the use of common physics

	packages (via CCPP) can be leveraged for optimizing ensemble Hurricane forecasts. NOAA and the US Navy can also collaborate on exploring and leveraging coupled/ocean/wave data assimilation methods for coupled Tropical Cyclone forecasts using COAMPS-TC and HAFS. Through IFEX, HFIP is already collaborating with the US Navy on ONR's TCRI experiment to collect observations that can be used to evaluate COAMPS-TC, HWRF, and HMON's ability to forecast RI. NOAA and the US Navy are also collaborating on exploring the use of ocean gliders to improve the coupled Tropical Cyclone forecasts using COAMPS-TC and HAFS. The successful interaction between OAR, NOS, and the Navy led to the largest deployment ever of uncrewed systems in tropical storm environments in FY20 and FY21.
5.4 Building a Focused Collaborative Network: 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	Through IFEX, HFIP provided a means for NOAA to partner with other Agencies (ONR, NASA, and NSF) to increase the capacity to collect observations in TCs to accelerate model development, evaluation, and analysis to initialize the hurricane forecast models. In 2021 IFEX is partnering with ONR's TCRI and NASA's Convective Properties Experiment (CPEX), and in 2022 with GOMO's EEOOTT. The FY18 and FY19 Disaster Supplemental resources are supporting deployment of gliders, drifters and sail drones and other new observational technologies targeted to improve hurricane forecasting. IOOS and OAR-GOMO continue to invest in ocean observing systems, including many benefits to hurricane forecasting. However, Supplemental funding and IOOS and GOMO investments are not sustained, which hinders continuous outyear operations of uncrewed ocean observing systems (e.g. gliders) at levels effective to meet model improvement goals. These challenges are recognized, and HFIP and the EEOOTT Resource Working Group are investigating investment opportunities across NOAA to leverage and procure resources to fill

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.	gaps in the hurricane intensity forecasting space (observing platforms, data assimilation needs, impact studies, etc.). As HFIP increases support for research into TC hazards at landfall, IFEX is evolving into the Advancing Prediction of Hurricane Experiment (APHEX) with closer ties to the partners supporting the observation program for the COASTAL Act.

Acronym

ALAMO	Air-Launched Autonomous Micro Observer
AOML	Atlantic Oceanographic and Meteorological Laboratory
COAMPS	Coupled Ocean/Atmosphere Mesoscale Prediction System
DA	Data Assimilation
ECMWF	European Centre for Medium-Range Weather Forecasts
EEOO	Extreme Events-Ocean Observations
EEOOTT	Extreme Events-Ocean Observations Task Team
EFSOI	Ensemble Forecast Sensitivity Observation Impact
EPIC	Earth Prediction Innovation Center
FSU	Florida State University
FV3	Finite Volume Cubed-sphere
GOMO	Global Ocean Monitoring and Observing
HAFS	Hurricane Analysis and Forecast System
HEOB	Hurricane Executive Oversight Board
HFIP	Hurricane Forecast Improvement Program
HMON	Hurricanes in a Multi-scale Ocean coupled Non-hydrostatic model
HPC	High performance computing
HRD	Hurricane Research Division
HWRF	Hurricane Weather and Research Forecasting
HYCOM	HYbrid Coordinate Ocean Model
IOOS	Integrated Ocean Observing System
IMPACT	Integrated Modeling Prediction Assimilation Coordination Team
JCSDA	Joint Center for Satellite Data Assimilation
JEDI	Joint Effort for Data Assimilation
JHT	Joint Hurricane Testbed
JTTI	Joint Technology Transfer Initiative
JTWC	Joint Typhoon Warning Center
LETKF	Local Ensemble Transform Kalman Filter
NCAR	National Center for Atmospheric Research
NCEP	National Centers for Environmental Prediction
NHC	National Hurricane Center
MOM6	Modular Ocean Model - 6

NRL	Naval Research Laboratory
NAS	National Academy of Sciences, Engineering and Medicine
OSE	Observing System Experiment
OSSE	Observing System Simulation Experiments
RTOFS	Real-time Ocean Forecast System
R2O	Research to Operations
TC	Tropical Cyclone
UFS	Unified Forecast System
WSRA	Wide Swath Radar Altimeter
WW3	Wavewatch3
WWCB	Weather Water Climate Board