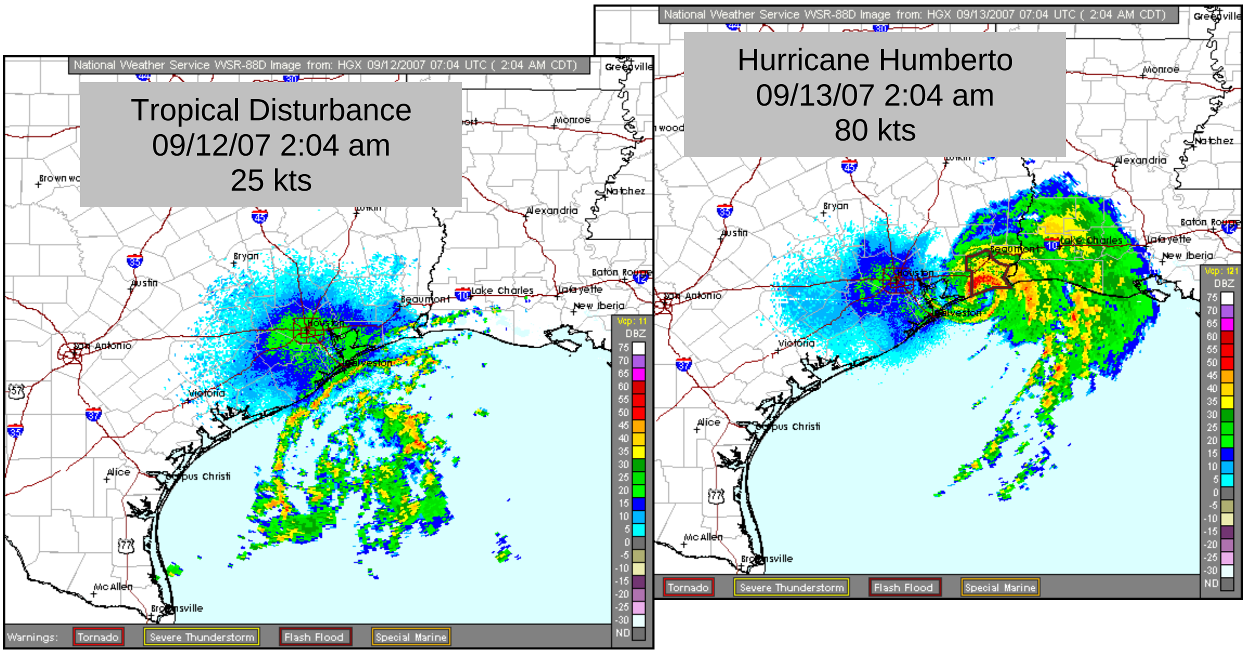
Proposed Framework for Addressing the National Hurricane Research and Forecast Improvement Initiatives

NOAA's Hurricane Forecast Improvement Project

July 18, 2008



Cover: Maps showing the radar reflectivity (dBZ) from the Houston, TX WSR-88D (HGX) at two times during the life cycle of Hurricane Humberto. The map on the left shows the early stage of a tropical disturbance on September 12, 2007, situated along the Texas Gulf coast, a weak and poorly organized system and the estimated wind speed (intensity) of 25 kts. The map on the right is 24 hours later on September 13 2007 showing a well-defined eye and eyewall structure of hurricane Humberto with a wind speed (intensity) of 80 kts. making landfall on the Texas coast northeast of Galveston, TX.

EXECUTIVE SUMMARY

The National Oceanic and Atmospheric Administration (NOAA), as the official national source of hurricane forecasts and in concert with other national planning efforts through the Office of the Federal Coordinator for Meteorology and the National Science Board, proposes a way forward through the development of the NOAA Hurricane Forecast Improvement Project (HFIP). The HFIP will 1) provide the basis for NOAA and other agencies to work towards a national effort to coordinate national hurricane research needed to significantly improve guidance for hurricane track, intensity, and storm surge forecasts, and 2) engage and align the inter-agency and larger scientific community efforts towards addressing the challenges posed to improve hurricane forecasts. The goals of the HFIP are to improve the accuracy and reliability of hurricane forecasts; to extend lead time for hurricane forecasts with increased certainty; and to increase confidence in hurricane forecasts. These efforts will require major investments in enhanced observational strategies, improved data assimilation, numerical model systems, and expanded forecast applications based on the high resolution and ensemble based numerical prediction systems.

The expected outcomes of the HFIP are high quality information with associated probabilities on high impact variables such as wind speed, precipitation, and storm surge. This will be achieved by reducing the average errors of hurricane track and intensity forecasts by 50%, improving the skill in forecasting rapid intensity changes (both increases and decreases), and by improved storm surge forecasting. The benefits of HFIP will significantly improve NOAA's forecast services through improved hurricane forecast science and technology.

Specific metrics include:

- Reduce average track error by 50% for Days 1 through 5.
- Reduce average intensity error by 50% for Days 1 through 5.
- Increase the probability of detection (POD) for rapid intensity change to 90% at Day 1 decreasing linearly to 60% at Day 5, and decrease the false alarm ratio (FAR) for rapid intensity change to 10% for Day 1 increasing linearly to 30% at Day 5.
- Extend the lead time for hurricane forecasts out to Day 7.

While improving the POD and FAR for rapid intensity change within 1 day of landfall is a high priority, given the uncertainty in track forecasts of landfall, these improvements are needed at all lead times over the entire life span of the storm system.

Furthermore, NOAA recognizes that addressing the broad scope of the research and technology challenges associated with improving hurricane forecasts requires interaction with, and support of, the larger research and academic community, including the open access to the data involved in this endeavor.

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FOREWORD

Since 1990, hurricane forecast track accuracy has been increased by about 50% through the use of enhanced observations, improved model guidance, and increased forecaster expertise. However, little progress has been made during this period on increasing the accuracy of intensity[1] forecasts. With recent catastrophic events like Katrina (2005) and Wilma (2005), back- to-back Category 5 storms in the Caribbean Sea like Dean (2007) and Felix (2007), and rapid intensifying storms just prior to landfall like Charley (2004) and Humberto (2007), *the time is now for NOAA and its partners to undertake an aggressive effort, with commensurate investments, to improve its hurricane forecasting capability*.

This message and sense of urgency is consistent with recommendations from 3 recent reports:

- The **NOAA Science Advisory Board Hurricane Intensity Research Working Group (HIRWG)** which recommended, "NOAA should allocate sufficient resources and provide national leadership to enable the high-priority research-and-development activities recommended below [in their 2006 report] to be undertaken at a sufficient level to ensure positive outcomes."
- The 2006 report of the **National Science Foundation (NSF) National Science Board (NSB) - Hurricane Warning: The Critical Need for a National Hurricane Research Initiative** calls for an additional $300 million annually over the next 10 years for hurricane science and research and names NOAA as a potential co-lead with NSF and other organizations to develop and implement a National Hurricane Research Initiative (NHRI). The NSB report led to the introduction of Congressional language (S.931 and HR.2407) supporting the NHRI, and placing NOAA in a leadership role.
- The 2007 report issued by the **Office of the Federal Coordinator of Meteorological Services (OFCM) - Interagency Strategic Research Plan for Tropical Cyclones - The Way Ahead** calls for a federal investment of $70-85 million annually over the next 10 years for tropical cyclone research and development; transition of research to operations; and operational high performance computing. NOAA has a major leadership role in the execution of this strategic, interagency research plan.

In addition, numerous studies and reports have shown that investments in forecasts and other warning information needed for community planners have a significant return for the Nation.

- A 2007 report from the National Hazards Review[2] states "…forecasting in the late 20th century prevented 66-90% of the hurricane-related deaths in the United States that would have resulted from techniques used in the late 1950s, but it is difficult to demonstrate an effect on property damage."
- A report from the Multihazard Mitigation Council (MMC) of the National Institute of Building Sciences concluded that, "…a dollar spent on mitigation saves society an average of $4."[3]

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[1] Hurricane intensity defined as the peak 1 minute sustained 10 meter wind speed (National Weather Service Manual 10-604, ***Tropical Cyclone Definitions***, June 8, 2004 http://www.weather.gov/directives/010/archive/pd01006004c.pdf)

[2] Willoughby, H. et al., "Hurricane Forecasting: The State of the Art", National Hazards Review © ASCE, August 2007, p.45-49.

[3] http://www.nibs.org/MMC/MitigationSavingsReport/Part1_final.pdf

Understanding the significant national need and building on recommendations from the recent reports, NOAA established the Hurricane Forecast Improvement Project (HFIP) to develop a unified 10-year plan to improve one to five day tropical cyclone forecasts, with an emphasis on rapid intensity change. The focus of the HFIP is to facilitate and translate basic and applied research towards improving specific forecast goals. The transition of research to operations is urgently needed to meet these national challenges and requires infrastructure enhancements and accelerated operational upgrades and related dedicated maintenance. In the near-term, NOAA is committed to strengthening its infrastructure through steady and measured improvements. In the longer-term, NOAA recognizes the benefits gained through accelerated, potential breakthrough advances in science and technology ranging from sophisticated coupled numerical models covering the earth system to the simple, analytical and statistical methods related to flow improving our understanding of flow regimes associated with intensifying hurricanes. To this end, NOAA is pursuing operational system architecture that can accommodate quantum leaps in research and technology.

The scope of HFIP encompasses the optimization and use of observations, emphasis on data assimilation techniques, upgrades to the numerical modeling systems, and improvements to forecaster applications. The desired outcome is to ultimately reduce the Nation's risk to hurricane impacts by delivering improved forecasts and tools for community planners and other decision-makers. The anticipated societal benefits will reduce deaths, injuries and property damage, and reduce the other costs associated with hurricanes by enabling decision makers to better identify at-risk populations and property, and by raising the confidence levels to initiate mitigation measures further in advance of approaching hurricanes than is currently practical. Furthermore, NOAA recognizes that addressing the broad scope of the research and technology challenges associated with improving hurricane forecasts requires interaction with, and support of, the larger research and academic community, including the open access to the data involved in this endeavor.

I. INTRODUCTION

During the past 15-20 years, hurricane track forecasts have steadily improved. Nevertheless, during this same timeframe hurricane intensity forecasts have shown little to no improvement. More importantly, recent cases of rapid intensity changes at or near the U.S. coastline have occurred with little or no warning. With more than 50 percent of the U.S. population living within 50 miles of the coast,[4] and with 180 million people visiting the coast annually, the risk to our Nation's coastal areas continues to grow. As the U.S. coastline continues to develop, more people will be at risk and impacts are likely to increase. In addition, annual U.S. hurricane losses average about $10 billion and a recent historical analysis of hurricane damages from 1900 to 2005 suggests a doubling of economic losses from landfalling hurricanes every ten years.[5] The need for substantial improvements, above and beyond current research efforts, in hurricane track and intensity forecast capabilities has never been greater.

1.1 The need for improved hurricane forecasts

> *"Billions of tax dollars have been provided for rescue, recovery, and rebuilding after hurricanes strike…recent hurricanes have focused public attention on the imperative to enhance our understanding of tropical weather systems and their multi-faceted impacts, ranging from geophysical and engineering elements to human economic dimensions….improving our nation's ability to become more resilient to hurricane impacts."* [6]

The emergency management authorities at the national, regional and local levels echo the importance and trust this nation places on hurricane forecasts. The coastal population explosion (Figure 1) over the last half-century translates to increased risks and to strong demands to extend hurricane forecast lead times that are necessary to evacuate some coastal locations that now require evacuation "orders" be issued 48 to 72 hours in advance. Therefore, more certainty in hurricane track and intensity forecasts is required, and these forecasts need to be extended beyond Day 5 for timely decision-making to reduce the risk to life and property, and to mitigate the losses incurred in the economic sectors. Highly accurate hurricane forecasts are used to ensure credible hurricane watches and warnings are issued in a timely manner. Accurate hurricane watches and warnings have become an essential factor in avoiding injury and loss of life and has reduced property loss and economic disruption.

The expected outcomes of the HFIP are to provide higher quality information contingent upon enhancement of current capabilities[7] (e.g. data collection and observations, data assimilation and modeling techniques, transition of hurricane research into forecast and warning operations, along with education, training, and outreach) with associated probabilities on high impact variables, such as wind speed, precipitation, and storm surge that can be used with longer lead times for more focused areas in order for the emergency

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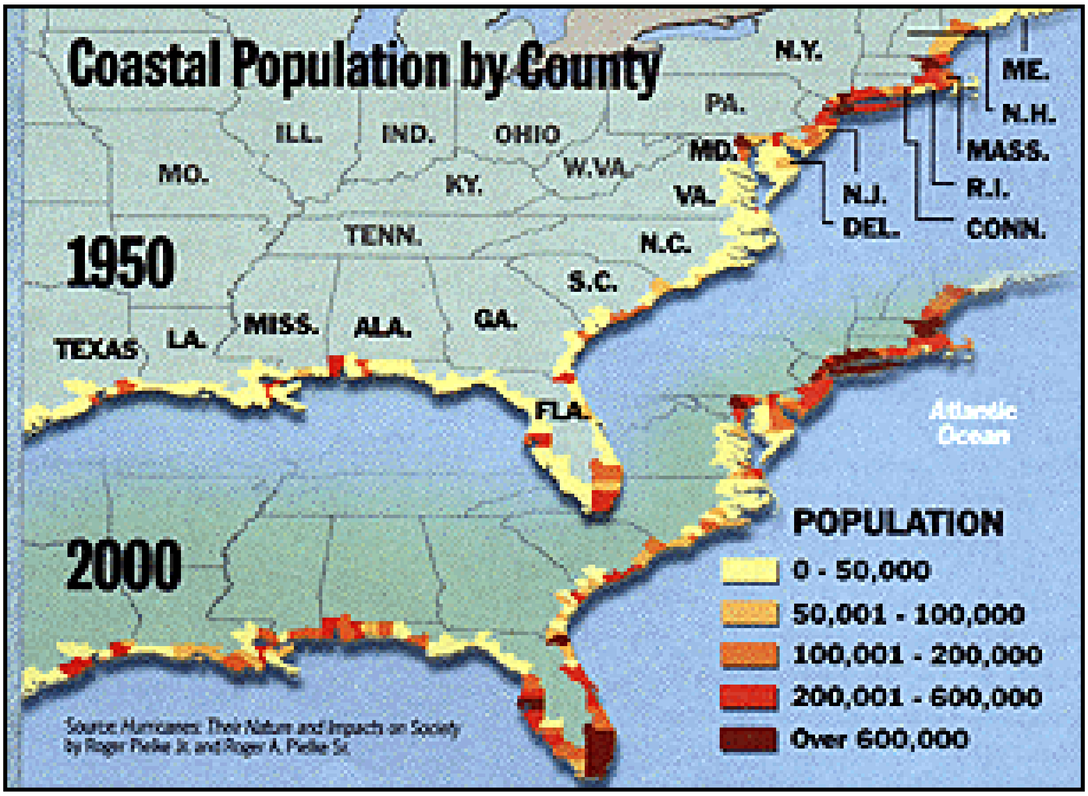
[4] http://www.ofcm.noaa.gov/p36-isrtc/fcm-p36.htm

[5] Pielke, R. A., Jr., J. Gratz, C. W. Landsea, D. Collins, M. Saunders, and R. Musulin, 2007: Normalized Hurricane Damages in the United States: 1900-2005. Accepted for publications in the *Bull. Amer. Met. Soc.*

[6] *Hurricane Warning: The Critical Need for a National Hurricane Research Initiative*, National Science Board NSB-06-115, January 12, 2007

[7] defined in Chapters 2 and 3 of the Office of the Federal Coordinator for Meteorology (OFCM) P-36, 2007; *Interagency Strategic Research Plan for Tropical Cyclones - The Way Ahead*



management community and the general public to take necessary decisive action to save lives and mitigate economic loses.

Figure 1. Coastal population by county. Source *Hurricanes: Their Nature and Impacts on Society*, by Roger Pielke, Jr. and Roger A. Pielke, Sr.

1.2 Operational Needs

The operational needs, developed by the tropical cyclone operations centers (NHC, CPHC, JTWC) are summarized in Table 1 adopted from the Office of the Federal Coordinator for Meteorology (OFCM) report, *Interagency Strategic Research Plan for Tropical Cyclones – The Way Ahead*. These operational needs support the overarching goal of high quality wind speed, precipitation, and storm surge analysis and forecast information with associated probabilities for use by emergency and other decision making managers. To meet these operational needs, focused applied research and transition efforts are required to improve numerical prediction models and data assimilation schemes, advance observations and observational strategies, expand forecaster tools, and properly apply human and infrastructure resources - all critical steps to ensure the future success of the nation's hurricane forecast and warning program. To improve our hurricane forecast prediction capability, a broad range of prediction techniques from simple analytical models to the more sophisticated earth system models will be considered. The focused enhancement of current research capabilities along with reductions of current operational limitations represents the underpinning premise of the HFIP plan. Ideally, the incorporation and use of such a balanced approach is expected to lead to an optimum mix of predictive techniques and allow for even break-through and novel prediction methods to compliment the predictive capabilities and associated methods in use today.

Table 1. Operational Needs Relevant to the Scope of the HFIP identified by the Hurricane Forecast and Warning Centers (NHC, JTWC, and CPHC), adopted from Table 4-1 of the OFCM Strategic Plan (Office of the Federal Coordinator for Meteorology (OFCM) P-36, 2007; *Interagency Strategic Research Plan for Tropical Cyclones - The Way Ahead*)

Priority	Operational Needs	Category[a]
1	Guidance for hurricane intensity change, with highest priority on the onset, duration, and magnitude of **rapid intensification** events. Similar guidance is also needed on when rapid over-water weakening will occur.	I
2	Improved observational systems in the storm and its environment that provide data for forecaster analysis and model initialization.	O
3	Statistically-based real-time guidance on guidance for track and intensity (e.g., multi-model consensus), provided to forecasters in probabilistic and other formats.	I, T
4	Improved storm surge guidance models, including guidance on breaking waves and featuring high-resolution input and output (including probabilistic formats).	SG
5	Operational analysis of the surface wind field (including maximum sustained winds) in hurricanes. This also includes methods for forecasting the wind field over elevated terrain and high-rise buildings.	O, I, S, A
6	Guidance for changes in tropical cyclone size/wind structure and related parameters, including combined sea heights.	S, SS
7	Improved utility of microwave satellite and radar data in tropical cyclone analysis, particularly to determine structure and intensity.	O, I, S
8	Probabilistic forecast guidance for hurricane surface wind speed.	I, S
9	Identification, and then reduction of, the occurrence of guidance and official track outliers, focusing on both large speed errors (e.g., accelerating and stalling storms) and large direction errors (e.g., loops), and on specific forecast problems, including interactions between upper-level troughs and hurricane, track forecasts near mountainous areas, and extra-tropical transition.	T, I
10	Improved techniques for estimating the intensity of tropical cyclones passing over and north of sea-surface temperature gradients (e.g., in the eastern North Pacific Ocean and the Atlantic Gulf Stream).	I

[a]Category abbreviations: A = Automation; I = Intensity; O = Observations; S = Structure; SG= Storm Surge; SS = Sea State; T = Track.

The advancement of the cumulative predictive capabilities beyond current forecast and warning capabilities to meet future, overarching societal needs requires a research focus as described below.

1.3 Research Focus

The OFCM Strategic Research Plan mapped the operational forecast needs into current research focus areas (Appendix outlines the HFIP portfolio) that are categorized into the following research topics:

- Conduct basic research on the processes that contribute to rapid intensification and on the theoretical limits of predictability,

- Optimize exploitation of current and planned observing systems for both research and operations; Identify observational gaps and develop initiatives to address those with significant potential,
- Improve data assimilation to fully exploit all in situ and remotely sensed data for both research and operational forecast,
- Improve numerical and other models for operational use to reduce error in track and intensity guidance, quantify uncertainty in these forecasts, and extend the timeframe for useful predictions related to hurricane development, evolution, and decay; build in the capacity to represent the physical processes responsible for rapid intensity change, and
- Expand and enhance forecast tools and applications to add value to the model guidance and direct use of observations by the forecasters and diverse user community.

The HFIP portfolio (Appendix) aligns current research and operational capabilities with the primary focus to meet future operational needs by focusing efforts and resources on research priorities in the atmospheric, oceanic, and computer/engineering sciences, many of which were identified in the OFCM Strategic Plan, and are listed in Table 2. Most of the list are directly relevant to meeting the goal and objectives of the HFIP.

Table 2. Research Priorities in Atmospheric and Ocean Science, adopted from Table 5-1 of the OFCM Strategic Research Plan (Office of the Federal Coordinator for Meteorology (OFCM) P-36, 2007; *Interagency Strategic Research Plan for Tropical Cyclones - The Way Ahead*)

Research Topics	**Type of Research** B = Basic; A =Applied
General research and numerical prediction topics	
1. Role of inner core processes on intensity and structure changes (e.g., eyewall replacement cycles, mixing).	B
2. Relative role of vortex versus environment in influencing intensity and structure (e.g., role of vortex mixing and resiliency [vortex Rossby waves and stability]).	B,A
3. Role of rainbands on intensity and structure changes.	B
4. Role of dry air, midlevel easterly jet, and suspended mineral dust from Saharan Air Layer on intensity and structure changes.	B,A
5. Role of vertical shear of horizontal wind on intensity and structure changes.	B,A
6. Tropical cyclone genesis.	B,A
7. Determinants of structure and relationship with preexisting wave disturbance; relationship between structure and intensity.	B
8. Role of ocean; role of oceanic heat content.	B,A
9. Physics a. Relative importance of physics (e.g., air-sea fluxes, microphysics, convection) on intensity and structure changes in various environments (e.g., sheared vs. non-shear) b. Processes within atmosphere-ocean boundary layer on intensity/structure changes (i.e., momentum and enthalpy fluxes); role of boundary layer wind structure on the transfer of energy and mass. c. Role of radiation and interaction of radiation with microphysics. d. Role of vortex-scale moisture convergence and cloud microphysics in precipitation processes. e. Role of landfall effects (e.g., surface flux changes) on intensity, structure, and precipitation processes. f. Resolution studies (considering a-e above) to determine what scales can be explicitly resolved.	B,A

10. Theoretical limits to tropical cyclone forecast errors for track, intensity, and structure.	B
Numerical prediction development topics	
1. Tropical cyclone vortex initialization; ocean initialization	A
2. Atmosphere-ocean boundary layer for coupled air-sea-wave problem; momentum (wave-induced drag) and enthalpy fluxes (sea spray complexity).	B,A
3. Land surface coupling: Complexity of coupling with HWRF; sensitivity of LSM on track, intensity and structure, precipitation	A
4. Coupling of HWRF with hydrology/inundation models.	A
5. Verification for three dimensional, high-resolution numerical prediction model for all phases of the tropical cyclone life cycle; varying atmosphere/ocean environment.	A
6. Diagnostic techniques to further increase the utility of global models (e.g., NCEP, UKMO, NOGAPS) in forecasting tropical cyclone genesis.	A
7. Development of advanced, high-resolution probabilistic guidance (e.g., ensembles); optimal ensemble construction and configuration; value of very high-resolution deterministic forecasts vs. ensembles	A
Observations and observing strategies	
1. Where to take observations for initialization of hurricane vortex; what is the hurricane "core" circulation and how do we define?	A
2. Alternatives and tradeoffs for observing storms and their environment with in situ (e.g., buoys, aircraft) and remote sensors (e.g., satellite).	A
3. Required observations to support model diagnostics and verification (e.g., IFEX effort led by HRD).	A
4. Techniques to evaluate the uncertainty and representativeness of observations and use of observations for initializing NUMERICAL PREDICTION models.	A
5. New observational technologies.	B,A

II. NOAA'S ROLE: HURRICANE FORECAST IMPROVEMENT PROJECT (HFIP).

2.1 Background – Establishment and scope

2.1.1 Building off the nation's interagency strategic research plan

The National Oceanic and Atmospheric Administration (NOAA) is working to build upon recent planning efforts of the National Science Foundation, National Science Board (NSB) and the Office of the Federal Coordinator for Meteorology (OFCM)[8], and proposes a framework with this document to engage the broader research community to improve the hurricane forecasts. The NOAA effort encompasses improvements to understanding, observing systems, data assimilation, numerical models, and forecaster applications. The ultimate goals are to: 1) improve the accuracy, reliability, and extend the lead time for forecasts of hurricanes; 2) increase confidence in those forecasts by customers and decision makers, especially those in the emergency management community.

The framework proposed, centered on operational hurricane forecast improvements, also includes important research contributions and technological advancements within NOAA,

[8] - Office of the Federal Coordinator for Meteorology (OFCM) P-36, 2007; *Interagency Strategic Research Plan for Tropical Cyclones - The Way Ahead.*
- National Science Board, 2007; *Hurricane Warning: The Critical Need for a National Hurricane Research Initiative.*
- National Oceanic and Atmospheric Administration Science Advisory Board, Hurricane Intensity Research Working Group Majority Report

and from other federal agencies, and academia. Within this planning process, NOAA seeks a partnership among the federal and academic communities to align the broader science and engineering community with the operational community in effort to realize the greatest benefits for the country. Without the broader community, addressing the critical hurricane research challenges will not be possible and the opportunity to transition new research and technology into operations will be diminished. With the partnership envisioned through this initiative (and consistent with the OFCM Strategic Research Plan), the entire spectrum of research from basic to applied can be brought to bear on operations.

As the federal agency tasked with issuing operational hurricane forecasts and warnings, NOAA is proposing a framework anchored on requirements developed under the auspices of the OFCM Strategic Plan to accelerate advancements in hurricane forecasts and warnings. Following the OFCM strategic planning process, NOAA established the Hurricane Forecast Improvement Project (HFIP) to develop a 10-year strategy to improve hurricane forecasts, with a focus on rapid intensity change.

2.1.2 Establishment of the HFIP

Recognizing the significance of the Hurricane Intensity Research Working Group (HIRWG) recommendations and stakeholder needs, the NOAA Annual Guidance Memorandum (AGM) for FY10-14 emphasized a need to address the findings and recommendations of the HIRWG of the NOAA Science Advisory Board.

> *The HIRWG reported its findings in July 2006 on the "state of the science" and current research and development (R&D) activities in NOAA and elsewhere with respect to hurricane intensity. It recommended an agenda of R&D activities directed to improve National Weather Service forecasters' skill in forecasting intensity and structure, and, in particular, rapid changes in intensity…*
>
> *The goal should be achieved by focusing research on the inner core of the hurricane using: advanced numerical weather prediction systems, with development and validation of high-resolution (1-km) hurricane forecasts (much finer than operationally feasible, without the acquisition of new, or reprioritization of existing, computing system capability); novel methods for data assimilation, to assimilate the diverse range of data that are available; improved observations of the hurricane and its environment; and applied R&D focused on understanding the phenomena related to predictability of rapid intensification and secondary eyewall phenomena. The HIRWG also identified the need for organizational changes to: (i) attain critical mass in the presently limited resources for both in-house hurricane modeling capabilities, and for interfacing with the wider research community; (ii) accelerate the transfer of research results to operations. The HIRWG also recommended the continued support of forecaster tools for tropical cyclone analysis and the improvement of simpler statistical and dynamical models that make use of advanced modeling system output.*

In addition to the emphasis within NOAA to respond to these recommendations, the U.S. Senate and U.S. House of Representatives introduced bills (S.931 and HR.2407, respectively) to establish the National Hurricane Research Initiative in response to the NSB report, which calls for NOAA and the NSF to provide the leadership in developing a strategy to address the hurricane research and development issues raised in the NSB report.

In response to the aforementioned national reports, stakeholder direction, Congressional interests, and internal program assessment, NOAA convened a corporate hurricane summit to develop a unified strategy to address hurricane forecast improvements. On May 10, 2007, the NOAA Executive Council (NEC) established the NOAA Hurricane Forecast Improvement Project (HFIP), a 10-year NOAA effort to accelerate improvements in one to five day forecasts for hurricane track, intensity, storm surge and to reduce forecast uncertainty, with an emphasis on rapid intensity change.

NOAA's HFIP requires an agency-wide integrated effort across programs. The participating programs will pursue the goals of HFIP by building upon their extensive expertise and existing activities and by collaborating with each other, other NOAA Goal Teams, other Federal, state and local agencies, academia, and the private sector.

2.1.3 Scope of the HFIP

The scope of the HFIP plan (Figure 1) encompasses research and development:

- To improve understanding, emphasis on the phenomena related to predictability of rapid intensity (RI)[9] change and secondary eyewall phenomena,
- To improve observations and observational strategies for the hurricane and its environment,
- Of novel methods for data assimilation, to assimilate the divers range of existing and new observations,
- Of advanced high-resolution numerical prediction and ensemble predictions systems for hurricane forecast guidance, and
- To accelerate the transfer of research results into operational forecasting.

While NOAA is developing its level of involvement in the broader spectrum of issues identified in the NSB report and is recommended to provide leadership in the national hurricane research initiative, NOAA focused the HFIP on the research and development issues identified by operational needs that will lead to improved forecast guidance and tools.

[9] Rapid intensification is defined at a 30kt increase of sustained maximum winds in 24 hours or less.

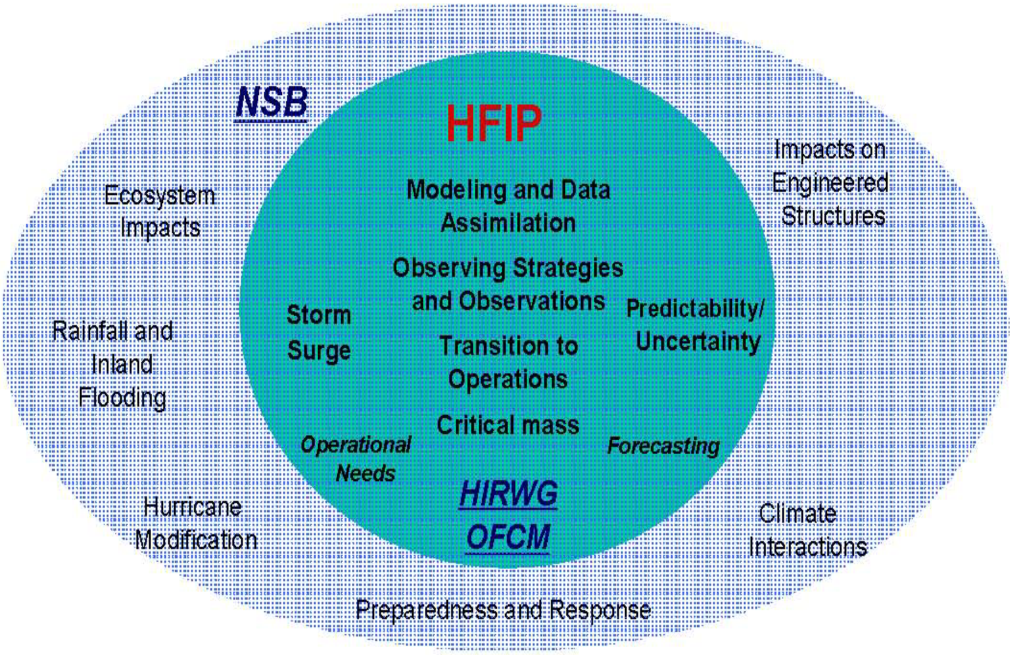


Figure 2. Scope of the NOAA Hurricane Forecast Improvement Project (HFIP).

2.2 Goals and metrics

2.2.1 HFIP Goal

The goal of HFIP is to improve the accuracy and reliability of hurricane forecasts and warnings and increase the confidence in those forecasts to enhance mitigation and preparedness decisions by emergency management officials at all levels of government and by individuals.

2.2.2 Metrics of the HFIP

The HFIP Plan aims to reduce and quantify the uncertainty in all forecast guidance, including high spatial/temporal resolution gridded wind speed, precipitation, storm surge analysis and forecast information, to be supported by the establishment of new aggressive metrics with a focus on rapid intensity change, which is the highest priority forecast challenge. These new metrics include:

- **Reduce average track error by 50% for Days 1 through 5 (Figure 3).**

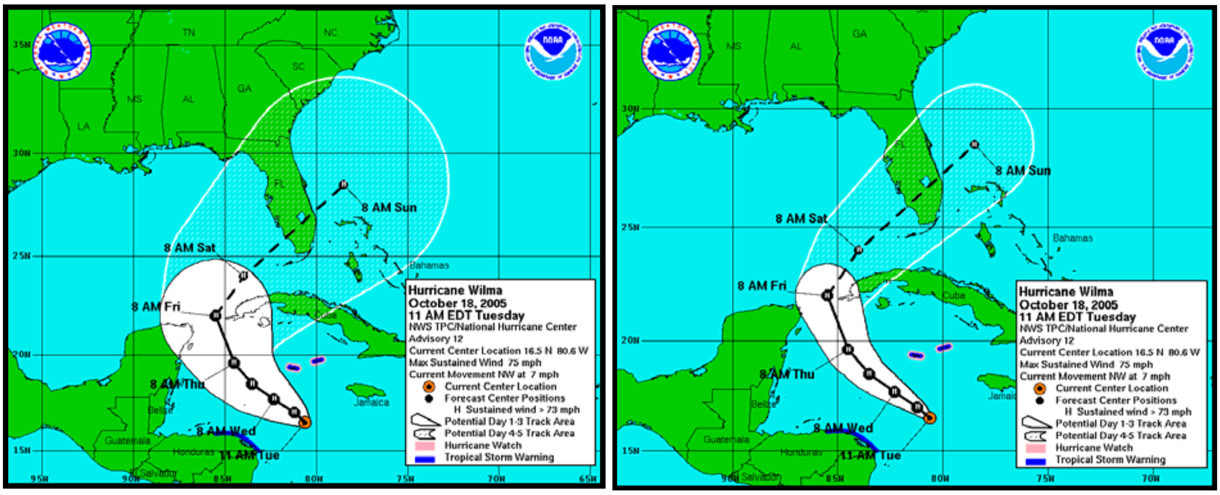


Figure 3. The panels above are examples of the NHC track forecast (cone graphic). The black line denotes the NHC forecast track for the center of the storm over a 5 day period The cone is calculated such that the center remains within it two-thirds of the time based on official forecast errors over the previous 5 years. The panel on the left shows what the NHC hurricane cone graphic would look like today. The panel of the right shows the same storm with a 50% reduction in track error, the first goal of the HFIP.

Based on input from emergency managers at all levels, the location of the tropical cyclone is most important, and over the past couple of decades the hurricane community has put most of its effort and resources into reducing the track error. While the limits of predictability for track error are not understood and could be limiting, NOAA will seek the same 50% level of improvement (preliminary warning reductions associated with a 50% track error reduction approach 80 miles as compared to a previous analysis of U.S. hurricane watches and warning from 2000-2006 showed and average storm-total watch length of 489 miles and an average storm-total warning length of 417 miles)[10] over next decade that it was able to achieve between 1990 and the present. More accurate information on the location of the storm will allow emergency managers to focus on a more precise coastal area at landfall.

- **Reduce average intensity error by 50% for Days 1 through 5**.

The current hurricane 48-hour official forecast intensity error is ~14 knots or roughly the wind speed range for one category on the Saffir-Simpson Hurricane Scale. Due to the uncertainty in today's intensity (strength of storm) forecast, NHC suggests that emergency managers prepare for one category above the NHC official intensity forecast (e.g., if NHC forecasts a Category 3 hurricane at landfall, emergency manager should prepare for a Category 4). A fifty percent reduction in intensity error will allow the emergency managers to prepare for the predicted intensity of the storm, not one over, in some cases. Reducing the uncertainty in the hurricane intensity forecasts, will positively impact an emergency manager's evacuation decisions in terms of the coastal and inland areas of greatest concern for both wind (Figure 4), and associated storm surge that is dependant on track and size of the storm as well as intensity (Figure 5).

[10] Mainelli, M., R.D. Knabb, M. DeMaria, J.A. Knaff, 2008: Tropical cyclone wind speed probabilities and their relationships with coastal watches and warnings issued by the National Hurricane Center. AMS 28th Conf. on Hurr. And Trop. Meteor., 28 April – 2 May, Orlando FL (http://ams.confex.com/ams/28Hurricanes/techprogram/paper_137827.htm).

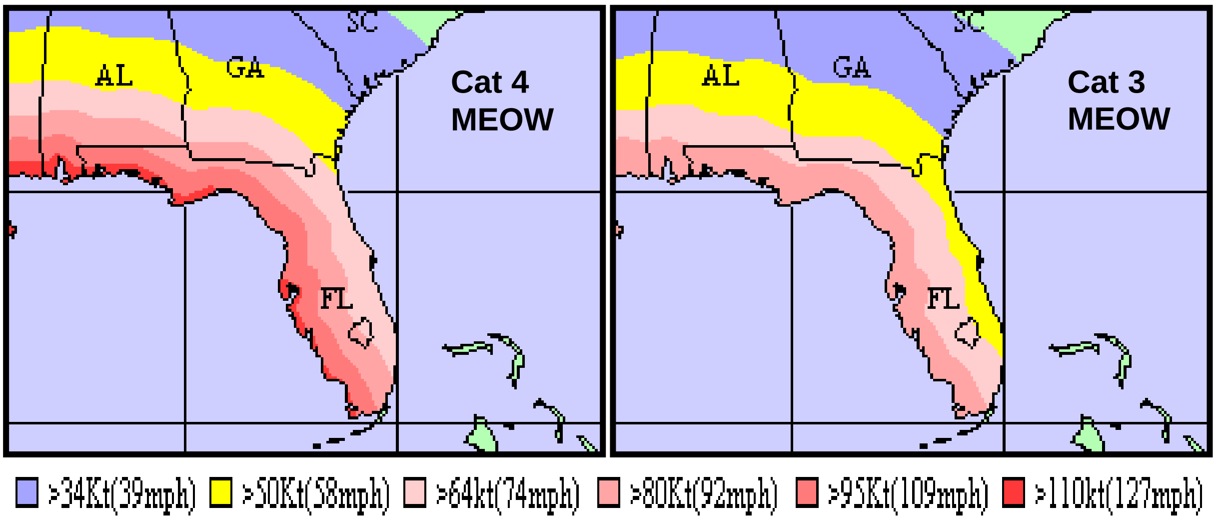
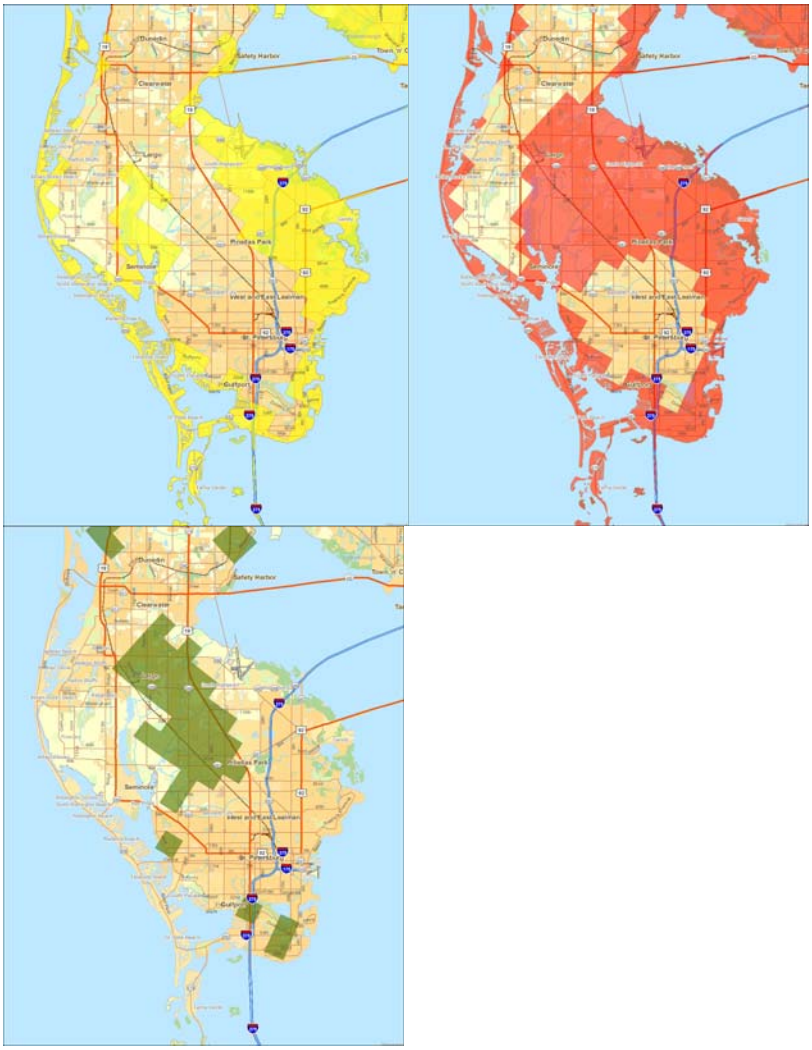


Figure 4: The Model Envelope of Winds (MEOW) shown above illustrates how far inland the winds of the hurricane will extend. The left panel shows the inland wind estimates for a Category 4 hurricane (moving at 14 mph) just prior to landfall. This is what the emergency managers would prepare for even though the official forecast calls for a Category 3 hurricane to account for the uncertainty in the intensity forecast. The success of this project would allow for emergency managers to prepare for Category 3 conditions when a Category 3 hurricane is forecast, which is represented in the panel on the right. In this example, both the east and west coast of Florida would prepare for less severe wind conditions.



(a) (b) (c)

Figure 5. Smaller preparation zone for storm surge over a portion of the Tampa Bay area resulting from improved intensity forecasts from the HFIP. Panel (a) shows in yellow the area of storm surge inundation potential from category 3 hurricanes. Panel (b) shows in red the area of storm surge inundation potential from category 4 hurricanes. The red also represents the area that must today prepare for a category 3 hurricane due to current intensity forecast limitations. Panel (c) shows in dark green the difference between panels (a) and (b). It represents the area—containing about 130,000 people—which today must prepare, but which might not be required (decision by emergency managers) to prepare as a result of HFIP. This translates to a savings of about $5 million in this area (reference pending), and a greater savings for the broader area affected by a hurricane. About $30 million per year on average would be saved for the United States assuming the decreased preparation occur 1/3 of the time (greater savings for greater application). In addition, many of those that will still need to prepare (yellow zone) will be able to prepare for one category lower storm surge depth than they do today. Further savings will occur as a result of narrowing the lateral area along the immediate coast designated to be at risk (e.g., Figure 3).

If the impacts of the first two metrics (50% improvement in track and intensity errors) are combined for the Gulf Coast examples in Figures 3 and 4, forecasts provided to the emergency managers would involve a more confined area of concern with a more precise wind estimate (Figure 6).

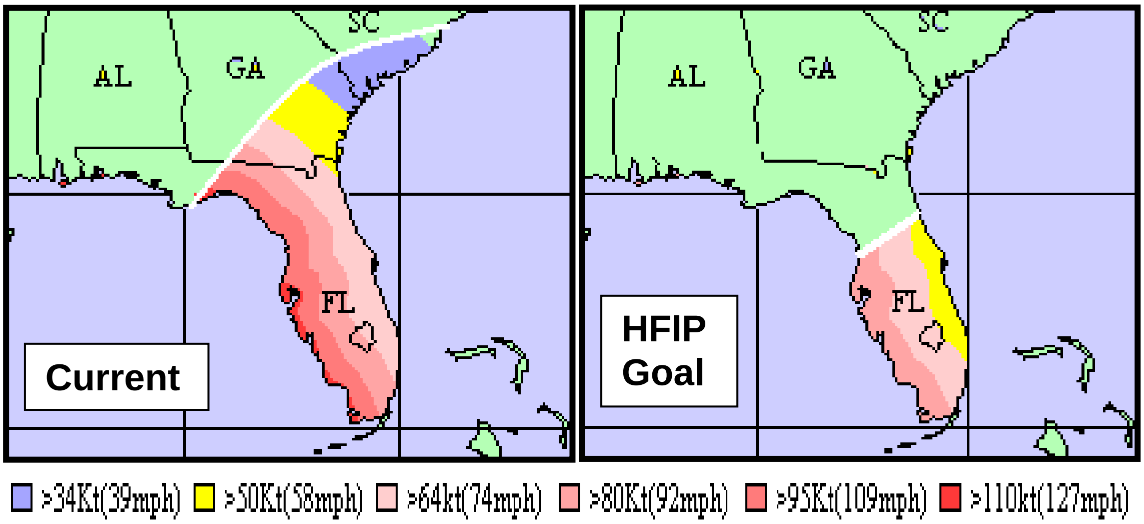


Figure 6: A depiction of a 50% improvement in intensity and track for the Gulf Coast cases shown in Figures 3 and 4. The HFIP goal (on the right) will allow a more focused effort by the emergency managers for their preparedness and evacuation activities.

- **Increase the probability of detection (POD) of RI change to 90% at Day 1 decreasing linearly to 60% at Day 5, and decrease the false alarm ratio (FAR) of RI change to 10% for Day 1 increasing linearly to 30% at Day 5.**

Rapid intensity change presents a great challenge to hurricane forecasters during the life of a storm and a serious problem for emergency managers when it occurs just prior to landfall. RI events represent approximately a two-Category change in 1 day, and have a significant impact on preparedness and evacuation actions for emergency managers.

The main hypotheses to explain rapid intensity changes in tropical cyclones focus on the development of vigorous convection in the presence of the enhanced circulation of the storms core[11]. The storm enters a vertical-plume-dominated dynamic regime on scales less than the storm scale (5-10 km), but larger than most convective scales (≤1 km). These moist plumes are stochastic nature, but a hypothesis put forward to be tested suggests that vortex development following prior convective events may play a critical role in providing a favorable environment for them to develop. However, the stochastic nature of such events may render the timing unpredictable[12]. Thus, a major research effort under the HFIP must address the predictability of these vortical-plume dominated regimes using ensemble and probabilistic approaches focusing on their probability of detection (POD).

The POD describes how likely we are to predict the occurrence of an RI event. The FAR is how often we "cry wolf" or predict an event to occur and it does not happen. Using the performance of a top performing intensity guidance model (Geophysical Fluid Dynamics Laboratory (GFDL) model) in predicting intensity changes >1 kt, >15 kts., and >30 kts. at all forecast lead times from one to five days, a new metric for rapid intensity change was developed. This metric calls for an increase in the POD of rapid intensity change to 90% with a FAR of 10% for a 1 day lead time, with the POD decreasing linearly to 60% and the FAR increasing linearly to 30% at day 5 (Figure 4).

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[11] For example Montgomery, M.T., M.E. Nicholls, T.A. Cram, and A.B. Saunders, 2006: A Vortical Hot Tower Route to Tropical Cyclogenesis. J. Atmos. Sci., 63, 355–386.

[12] Nguyen SV, Smith RK, Montgomery MT. 2008. Tropical cyclone intensification and predictability in three dimensions. *Q. J. R. Meteorol. Soc.* **134**: 565–584.

The current POD/FAR of GFDL model for rapid intensification events is 30%/80% at day 1 (goal is 90%/10%) and 0%/100% at day 5. Whereas, the current POD/FAR for the official forecasts are 9%/56% at Day 1, 3%/50% at Day 2, and 0%/100% at Day 3 and higher. Figure 4 shows a graphical depiction of this metric.

While improving the POD and FAR of RI change within 1 day of landfall is a high priority, given the uncertainty in track forecasts of landfall and the need by some to make decisions on protective actions more than one day before landfall, these improvements are needed at all lead times over the entire life history of the storm system.

Increasing the POD and decreasing the FAR of RI events can lead to greater confidence in forecasts by the users, which is a collective need of all levels of emergency managers.

- **Extend the lead time for hurricane forecasts out to Day 7 (Figure 7).**

NHC extended the lead time from three to five days in 2001, however state and federal emergency managers have expressed that five days is not enough time in certain areas due to population growth, infrastructure, resources, etc. Extending the forecast out to seven days (based on improvements to objective guidance and associated probabilities for when and where to issue hurricane watches and warnings out to 48 hours and beyond) serves to address the longer lead times required by emergency managers to plan for a landfalling tropical cyclone.

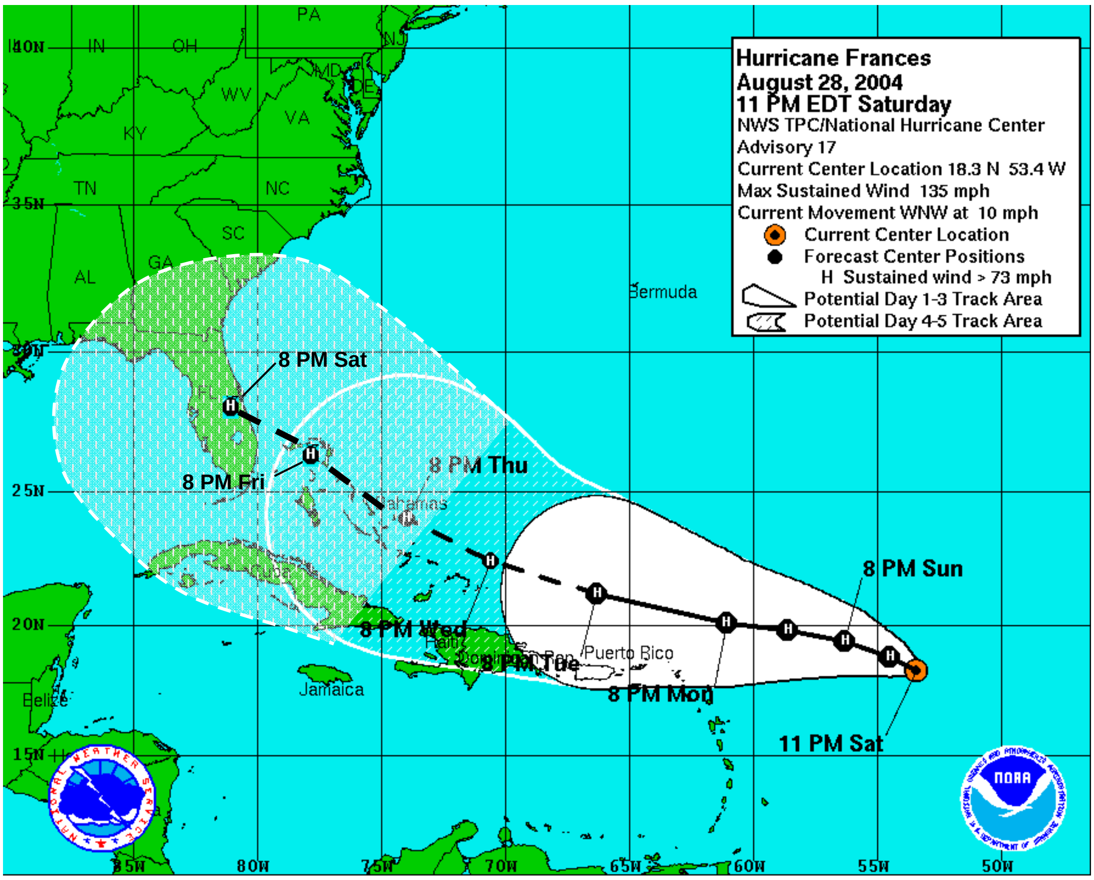


Figure 7. An example of a proposed 7-day NHC track forecast product.

2.3 Key strategies for the HFIP

Five key strategies consistent with the OFCM plan are defined to implement the activities needed to improve hurricane forecasts, with an emphasis on rapid intensity change.

2.3.1 Optimize observing systems for research and operations

Continuing to advance observational capabilities for tropical cyclone analysis, forecasting and numerical weather prediction is a vital component of the HFIP. There is a continuum from exploratory scientific research, conducted with new types and new generations of advanced instruments and platforms, to the proven operational systems relied upon for routine and severe-event analysis and forecasting. Over the past four decades and more, NASA research satellites and airborne observing systems developed and flown by NOAA and DOD partners have made major contributions to the operational systems.

To help meet the operational needs identified in Table 1 and research topics (Table 2), there are many planned observation platforms and instruments to enhance observing capabilities for hurricane forecasters and hurricane numerical prediction systems. With several new observational platforms and sensors potentially available in the next several years, *a capability is needed to evaluate the utility of observing platforms and instruments and advise NOAA on the its investment decisions* for improvements in tropical cyclone analysis, forecasting, and operational modeling. Activities to evaluate observing systems to determine the optimal systems/platforms for improvements in hurricane forecasts require the establishment of an observing system evaluation capability for hurricanes within NOAA (in coordination with the NOAA Observing System and Research Councils) to:

- Support NOAA in its investment decisions on observing systems and platforms,
- Set priorities for NOAA's investments to improve hurricane observing system analysis and the forecast guidance for intensity and rapid intensity change (e.g., Observing System Experiments (OSE) and Observing System Simulation Experiments (OSSE)),
- Define research & development agenda to improve hurricane observing systems for exploratory platforms (e.g., investigation of new satellite and unmanned observing systems through partnerships with NASA and DOD),
- Demonstrate the utility of observations to improve model guidance, and
- Define and execute targeted field experiments to focus on key physical processes to support model development.

This strategy builds upon NOAA's long-standing hurricane research and operational observing capabilities, focusing on developing a capability to evaluate the utility of existing and new observing capabilities to improve the hurricane forecast guidance.

2.3.2 Define and build the next generation hurricane forecast framework, including the Hurricane Forecast System/Global Forecast System (HFS/GFS)

The next generation hurricane forecast framework is defined as multi-model suite containing both high resolution and ensemble forecasts produced by NOAA and other numerical prediction entities on the national and international scales. Within this framework, a next-generation Hurricane Forecast System/Global Forecast System (HFS/GFS) will also be defined and constructed to accurately represent the physical processes responsible for rapid intensity change through HFIP focused (Table 2) priority research and development activities within NOAA and the broader research community. Associated research and development (R&D) activities include:

- Construct a multi-model ensemble system with
  - High quality numerical guidance collected from leading numerical prediction centers, including their high resolution control and ensemble suite.
  - Statistical post-processing of multi-model ensemble to bias correct and downscale from global to regional to local scales based on bias corrections from the multi-model ensemble forecast system
- Develop, test, and implement a version of the HFS at the resolutions necessary to adequately model hurricane structure, dynamics, eye wall replacement, etc.
- Improve formulation for modeling of the enthalpy flux transfers from the underlying ocean into the atmosphere.
- Improve the real-time ocean data assimilation system to improve the assimilation of altimetry and other observations. Additional work will be required using the proposed observing strategy analysis capability to define the necessary density of ocean observations to develop and maintain an adequate knowledge of the state of the ocean necessary to accurately predict the impact of the ocean on hurricane formation, size and intensity.
- Develop high-resolution hurricane ensembles to address the uncertainty of the model guidance. The use of multi-models will be used to define the uncertainty in the model guidance. The use of managed diversity in the ensemble scenarios to ensure the derived probability density functions (PDF) of the intensity errors accurately capture and bound the total error in the forecast system.
- Significant improvements in the performance of the NOAA GFS.
  - An end-state GFS modeling system[13] with resolutions close to 10 km globally will be required. Changes in the concept for using this system operationally include replacement of a single deterministic run of the model with the "most probable" forecast determined from a derived probability density function based on a set of ensemble scenarios set up to capture and bound the error in forecast from both the uncertainty in the initial conditions and the modeling system.
  - The use of managed diversity in the ensemble scenarios to ensure the derived probability density functions (PDFs) of the track errors accurately capture and bound the total error in the forecast system.
- Develop next generation hydrodynamic (i.e., storm surge and inundation) model (with the NOAA Storm Surge Transition Project)
- Make better use of today's massively parallel high performance computing systems to achieve significant run-time performance of the models. Systems in the near future will have 10's of thousands of processors running in parallel. To fully take advantage of these systems, re-engineering of the models will be required to extend the optimal parallel perform from a few hundred to several thousands of processors.
- Pursue an active process research and numerical modeling development effort on the following aspects of the hurricane problem:
  - Environmental forcing ("good" vs. "bad" trough interactions)
  - Convective Scale processes: organization of convection (eyewall vs.

[13] In partnership with the United States Navy and the Air Force, NOAA is planning to develop, test and implement the National Unified Operational Prediction Capability the future National global modeling system meeting NOAA, Navy and Air Force forecast guidance requirements

stratiform)

- Microphysics
  - Liquid vs. ice
  - representation of convection at high resolution (resolving cloud scale)
- Inner Core Region
  - Scale interaction – feedback between vortex dynamics, convective physics and environment
  - Adjustment processes – eyewall mixing and replacement cycles
- Air-Sea Interaction (oceanic/atmosphere boundary layer): Air-Sea fluxes (exchange coefficients) under disturbed conditions (e.g. sea spray)
- Turbulence and subgrid scale missing: upper ocean processes (depth of mixed layer, representation of oceanic circulations)

This strategy builds upon NOAA's long-standing operation numerical prediction capabilities and related research efforts to improve understanding the physical processes that lead to track, intensity/structure, and precipitation changes in hurricanes. This plan focuses on developing a capability to accelerate numerical modeling developments to accelerate improvements in the hurricane forecast guidance through enhanced research between NOAA and the larger research community.

As recommended by the HIRWG and OFCM reports, additional human and infrastructure resources (e.g., items such as computational power, network bandwidth, architectural/engineering requirements, and maintenance of applicable systems) will be necessary to support development, operations, and maintenance of advanced data assimilation and numerical modeling systems and other forecaster tools. In any development of advanced techniques, it is critical to have a balance of human and computing resources not only for the development and deployment of the initial implementation, but also for subsequent maintenance and future code enhancement activities.

The additional computational expense and code complexity of any advanced technique permeates the entire development and operational activities at an operational center. On the development side, all experiments must use a parallel version of an operational system. Experimental changes are therefore carefully controlled, and interpretation of results is facilitated. Due to the great complexity of modern numerical modeling forecast systems, diagnosing results requires a coordinated effort and relevant expertise for the coupled system across several scales of motion, as well as, the resources (infrastructure, computational, personnel, and budgetary) to run an adequate number of cases (often requiring several months of data assimilation).

Furthermore, the need for the use of an ensemble approach for all forecast applications, including hurricane forecasting, was highlighted by the National Research Council Report[14]. The report states, as one of their nine major recommendations, that *"NOAA should develop and maintain the ability to produce objective uncertainty information from the global to the regional scale."* Providing the ensemble information at a high resolution meeting the expectations of the users of hurricane forecasts will require significant additional computational resources.

[14] *Completing the Forecast: Characterizing and Communicating Uncertainty for Better Decisions Using Weather and Climate Forecasts*, National Research Council of the National Academies, ISBN 0-309-66261-3, 2006.

2.3.3 Institutionalize and fully fund transition of research to operations

The transition of research to operations – referred to by the OFCM and defined by the Board on Atmospheric Sciences and Climate, National Research Council as "bridging the valley of death" – requires robust interaction between the research and operational community, as well as a strong interface with the user community. It also requires a healthy infrastructure for the transition which would include resources and processes for evaluation and demonstration, operational implementation and operations and maintenance. The strategy revolves around the notion that to accomplish "R2O", we must support "O2R" needs to ensure that the transitions are successful. This strategy is imperative to realize the benefits of targeted research in operations. The activities are as follows:

Establish an end-to-end process to transition new observing systems and platforms and modeling improvements into operations including:
- Identify requirements
- Technology development and prototype options
- Demonstration and evaluation
- Build the system and implementation operationally
- Operations and maintenance

Establish research to operations activities for the Joint Hurricane Testbed (JHT) as part of base-funded operations and fully fund research to operations (R2O) needed to improve hurricane forecasts:
- Develop a portfolio of binding commitments (via the JHT Charter improvements) defining operational needs, research deliverables, and plans for sustained operations and maintenance associated with incorporation of the enhanced operational capabilities.
- Establish operations and maintenance (O&M) infrastructure, and support for upgrades to the JHT infrastructure

Broaden the JHT charter and increase support to put more emphasis on HFS research & development issues including:
- R&D for specific HFS improvements (including Hurricane Weather Research Forecasting model (HWRF))
- R&D to evaluate models
- R&D to develop new tools for forecasters
- R&D to test the utility of observing systems for operational platforms

Other activities focused on R2O include:
- Developing interactions between JHT and Developmental Testbed Center (DTC) and Joint Center for Satellite Data Assimilation (JCSDA) to address HFS issues.
- Expand DTC activities to support availability of HFS to research community
  - Provide current version of operational model system in repository, develop documentation and training material for HFS model system
  - Support and conduct workshops on operational HFS model system
  - Support research grants to test and improve HFS model system capability, particularly to investigate model predictability, trade-off between decreased grid-spacing and ensembles, impact of improved physics

packages/parameterization, impact of different model cores, ensemble approaches, and improved numerical techniques
    - Facilitate transition of research developments into operational model system

- Expand the JCSDA activities to support HFS and GFS improvements (will require expansion beyond satellites)
    - R&D (including OSSEs) to address data assimilation issues related to increasing diversity in remote sensing (e.g., satellites, radar) and in-situ data collection platforms (e.g., aircraft, buoys, etc.)

2.3.4 Increase High Performance Computing and Information Technology capacity and capability

High quality hurricane forecasting will require a significant increase in High Performance Computing (HPC) and Information Technology (IT) capabilities. The framework of combining information from different forecast centers involves virtual grid computing as the system leverages and relies on computing capability across the numerical prediction centers, but may require significant enhancements in telecommunication. In addition, each center, including the NOAA computing centers, will also require higher-resolution analyses and forecasts by running the numerical models on massively parallel processors (MPPs), including NOAA's supercomputer. Therefore, an increase in HPC capability and IT capacity is required to enable and support advancements in the NOAA HFS/GFS, including ensemble capabilities.

The implementation strategy is as follows:

Pursue the HPC improvements using two parallel approaches;

- Explore high capacity, operationally reliable, and cost effective telecommunication channels allowing the exchange of large amounts of hurricane-related gridded information among numerical prediction centers for forming the basis of a multi-model hurricane forecasting framework;
- Take advantage of the existing HPC infrastructure which we refer to as the "sustained" improvement – this includes the path currently in the NOAA plans to develop a 4 km HWRF with existing computational resources; and
- Develop an accelerated approach that utilizes the HPC infrastructure to provide the capability of running in an "on-demand" mode:
    a. A much higher resolution version of the HFS, concurrently with
    b. A high resolution ensemble

The benefit to NOAA of utilizing all three paths is that while it maintains the current HFS/GFS development strategy, it provides potentially large benefits from the multi-model approach through efficient data exchange. At the same time, it provides an opportunity in a short time (<5 years) to demonstrate a higher resolution capability sooner than along the sustained track. In addition this demonstration of an improved capability will serve as justification for the necessary HPC investments for higher resolution control and ensemble forecasts along the sustained track.

2.3.5 Broaden and access the expertise of the operational tropical/hurricane numerical prediction and research community and include stakeholders

NOAA clearly recognizes the broad scope of the scientific challenges associated with understanding and prediction hurricanes. Addressing these challenges and improving the forecasts of hurricane track and intensity will therefore involve significant interaction with the external community. In order to broaden and access the necessary expertise, NOAA envisions enhancing its hurricane-related research approach and expertise supported through its annual hurricane research program activities through the following actions as a fundamental part of HFIP:

- Broaden the base of expertise of the tropical cyclone operational numerical prediction and research communities and broaden access to R&D community
  - Establish a process to increase operational numerical modeling and tropical expertise through workshops, symposia, conferences, visiting scientist
  - Establish Science Advisory Committee composed of NOAA and representatives of the external R&D community to advise HFIP on scientific direction for the R&D investment and help to establish requirements for external development activities
  - Establish Technical Advisory Committee composed of NOAA and representatives of the external R&D community to advise the HFIP on standardized metrics and test cases for testing and acceptance of HFS updates
  - Grants/Contracts to support research and technology development and training activities for external community at NOAA operational facilities (e.g., visiting scientists, Post-Docs, graduate students, professors)
  - Outreach and education for operational modeling development activities to include expertise in physics, numerical techniques, coding for Message-Passing Interface (MPI), (e.g., workshops, conferences, publications)
  - Exploit the resources of existing mechanisms (e.g., via NOAA Science Advisory Board, the National Academy of Sciences Board on Atmospheric Sciences and Climate, and NOAA's internal Councils) to evaluate the progress and direction of the HFIP internally and with the external community. This is intended to include annual HFS R&D workshop focused on reviewing our progress, determining applications and techniques for R2O and O2R, and evaluating our goals and metrics.
  - Establish routine workshops/meetings for internal and external reviews on HFIP priorities and progress

- Interact with other federal, academic, and private sector research communities to leverage and coordinate research activities
  - Establish a mechanism to promote interaction of outside research community on HFS improvements (e.g. annual HFS research review at OFCM Interdepartmental Hurricane Conference
  - Support and advise NOAA leadership on interactions with the broader community with respect to tropical cyclone forecast improvement issues
  - Engage, align and leverage ongoing efforts of other R&D programs

2.4 Priorities, milestones, and investments of the HFIP

Tables 3, 4, and 5 include the short, mid, and long terms priorities and milestones for the HFIP Plan. Each set of priorities are categorized by implementation strategy. The milestones described are interdependent. If the short term investments are not made, it will take longer to reach the outcomes in the next tier.

The investments and timelines for each activity listed in Tables 3, 4, and 5 are being developed through NOAA and are contingent upon resource availability. A fully supported plan is designed to achieve the following benefits for NOAA:

- Improved hurricane forecast guidance
- Accelerated and streamlined the transition of research to operations and applications
- Establish capability for observing systems to advise NOAA on its investments to improve access, impact, and utility of observations for operations and research
- Developed strategy to increase high performance computing capacity and capability for hurricane forecasting (provide business case for investment)
- Expanded and developed tropical expertise for enhanced interaction with the operational modelling and research communities

TABLE 3. SHORT-TERM ACTIONS FOR HFIP:

PRIORITIES:	MILESTONES:
A. High Resolution Model and Other Model Enhancements ♦ Technical staff with modeling and software engineering expertise ♦ R&D for HFS/GFS, using DOE HPC system, to demonstrate high resolution and ensemble prediction capability, statistical post-processing, and address data assimilation challenges ♦ Planned HFS upgrades sustained ♦ Storm Surge Testbed	– Staffing computing infrastructure established to evaluate model improvements – Targeted high resolution and ensemble model research and development funded – Demonstration completed on the impact of forecast performance using the high resolution model system on DOE HPC system – decision point for NOAA HPC investment – Upgrades to HFS implemented operationally, and HFS/HWRF on a path to 4km resolution – Storm surge testbed established
B. Enhance HPC Capability ♦ NOAA R&D computing to support HFS/GFS development including software engineering	
C. Research to Operations (R20) Enhancements ♦ Increase funding for the JHT (including staff) ♦ Increase support for the DTC and JCSDA ♦ Targeted field programs and operational flights	– Staff and infrastructure established for enhanced transition of research to operations
D. Broaden expertise and expand interaction with external community ♦ Establish a visiting scientist/Post Doc program at research and operational centers ♦ Advisory committees, community workshops	– Broaden community expertise through visiting scientists at research and operational centers – Involvement with external community for modeling R&D and development of forecast tools through JHT, DTC, and JCSDA

TABLE 4. MID-TERM ACTIONS FOR HFIP:

PRIORITIES:	MILESTONES:
A. High Resolution Model and Other Model Enhancements ♦ Implement the higher resolution HFS and GFS for operations including associated IT infrastructure ♦ Implement next generation storm surge model(s)/ensembles ♦ Sustain HFS model research and development	– Operational implementation of a high resolution model system and next generation storm surge model, improvements to intensity forecasts – Operational implementation of a 4km HFS
B. Enhance HPC Capability ♦ Ramp up HPC investment for sustained NOAA operations, based on input from the HPC demonstration period	– Optimized process established to advise NOAA on observing investment decisions
C. Research to Operations (R20) Enhancements ♦ Establishment of observing system analysis capability, including demonstration, evaluation, transition, operations and maintenance ♦ Maintain increased level of support for the JHT, DTC, and JCSDA	– An enhanced JHT established for a more efficient transition of projects, yielding enhanced forecast tools and modeling improvements – New generation of operational modelers and tropical expertise underway
D. Broaden expertise and expand interaction with external community ♦ Ongoing external community involvement in NOAA operational and research facilities	– Community involvement in evaluation of HFIP

TABLE 5. LONG-TERM ACTIONS FOR HFIP:

PRIORITIES:	**M ILESTONES:**
A. High Resolution Model and Other Model Enhancements ♦ Continued improvements to the high resolution HFS and GFS for operations including associated IT infrastructure **B. Enhance HPC Capability** ♦ Sustained operational HPC capability **C. Enhance HPC Capability** ♦ Sustained operational HPC capability for high resolution models **D. R2O Enhancements** ♦ Sustained end to end transition process **E. Broaden expertise and expand interaction with external community** ♦ Ongoing process for external community involvement in NOAA operational and research facilities	– Healthy NOAA modeling and IT infrastructure for operations – Fully high resolution HFS/GFS sustained on sustained NOAA operational High Performance Computing – Integration of long lead observing improvements – Next generation of tropical experts and modelers – Forecast improvement goals met and customer needs addressed

III. STRATEGY AND PROPOSED FRAMEWORK TO ALIGN THE NATIONAL HURRICANE RESEARCH AND FORECAST IMPROVEMENT INITIATIVES

3.1 Strategy to align with the larger community

NOAA's mission-oriented requirements for operational system development, implementation and sustained operations compel the HFIP toward attaining a specific set of short-term forecast goals, related applied research focus areas and infrastructure investments. Within this mission-oriented context, the research and transition activities needed to improve operational forecasts are accomplished with the aid of testbeds strategically aligned with the needs of the forecast centers. In general, testbeds are a collaborative environment for conducting integrative research, for testing new ideas in an *end-to-end fashion* under the rigors of operational constraints (real and simulated), and facilitating the deployment into operational practice of knowledge gained in research (NSB Report 2007).

Testbeds such as the Joint Hurricane Testbed (JHT) in Miami, the Developmental Testbed Center (DTC) in Boulder, and the Joint Center for Satellite Data Assimilation (JCSDA) in Maryland are oriented towards improving operational hurricane forecasts and guidance. These testbeds provide evolutionary pathways to coordinate applied model and technology advancements to specific forecast requirements. These testbeds focus on identifying and effecting the transition of research and technologies capable of providing immediate and justifiable improvements to operational hurricane forecasts.

From this perspective, two complementary thrusts which operate in parallel are envisioned. An *evolutionary* thrust will partner with the research community to transition promising new research into operational services. NOAA's emphasis will be on transitioning research demonstrated to be within the realm of possibility into existing operational systems and will focus on what is needed to complement external research to meet specific operational needs. Where there is scientific potential demonstrated, NOAA will test and implement these advances into new operational systems.

NOAA also recognizes that in addition to the evolutionary changes noted above, a *transformational* thrust is also required to produce revolutionary breakthroughs that can influence future operational prediction. Realizing these gains tomorrow will require investments in basic and applied research today. NOAA will join forces with the external basic and applied research communities to meet these challenges.

Communication between federal partners and the external community on operational needs and associated research focus areas is necessary to achieve both immediate successes and scientific research advances that hold promise for the future. A highly visible and independent oversight activity will be identified. An annual interagency program review with a significant external (to NOAA) role is proposed at the Interdepartmental Hurricane Conference that leads up to an annual summit attended by agency, academia, and private sector research leadership.

Bridging across the OFCM and National Science Board reports, the NOAA HFIP plan involves evolutionary and transformational pathways that require coordination between key federal and academic leaders in order to properly support the required research and development and to improve the operational hurricane track and intensity forecasts. A formally established national alliance will ensure coordination across the broad spectrum of activities from observations to data assimilation to modeling to basic research. To outline the scope, the following table is a preliminary list of broadly defined mission areas of each organization. While improvements to hurricane track, intensity, precipitation, and storm surge forecast are sought in the near-term, it is the promise of break-through improvements in hurricane forecasting in the future that holds the key to aligning our national efforts and resources. The national alliance will need to develop potential roles and responsibilities, along with strategies and plans. In addition, efforts should be undertaken to explore the pros and cons of standing up an office to facilitate coordination and communication to align and leverage the resources available to address the national need.

Table 6. Broadly defined activities across the spectrum from basic research to end users of hurricane forecasts for the listed agencies.

<table>
<tr><th></th><th>Basic Research</th><th>Applied Research</th><th>Operational Implementation</th><th>Operations</th><th>User</th></tr>
<tr><td>NOAA</td><td>Mission-oriented fundamental research</td><td rowspan="3">• Fund & Conduct
• Instrument Development
• Process Studies
• Data Impact Studies
• Forecast Improvements
• Forecaster applications</td><td rowspan="2">Observations, Data Assimilation, Modeling</td><td rowspan="2">Forecasts, Watches and Warnings, Products and Services</td><td rowspan="3">• Emergency Managers
• Decision-Makers
• Federal, Private, and Public</td></tr>
<tr><td>U.S. Navy</td><td>Fund & Conduct</td></tr>
<tr><td>NASA</td><td>Fund & Conduct</td><td>Partners in the R2O process through JCSDA</td><td></td></tr>
<tr><td>NSF</td><td>Fund</td><td>Fund</td><td></td><td></td><td></td></tr>
<tr><td>FEMA</td><td></td><td></td><td></td><td>Products & Services</td><td>Emergency Response</td></tr>
<tr><td>DOE</td><td>Fund & Conduct</td><td></td><td></td><td>Supercomputing Applications</td><td></td></tr>
<tr><td>Academia</td><td>Conduct</td><td>Conduct</td><td rowspan="2">Partners in Testbeds</td><td></td><td></td></tr>
<tr><td>Private Sector</td><td>Conduct</td><td>Conduct</td><td></td><td></td></tr>
</table>

While institutions, groups and individuals in the scientific community may advocate specific approaches, techniques and both short and long term solutions, a singular truth prevails … a diverse combination of solutions is required to move the entire national enterprise forward to address this critical need of the nation.

3.2 NOAA infrastructure improvements

NOAA is addressing its infrastructure improvements to ensure research can be carried out and that new breakthroughs in research and technology can be accelerated into operational forecasting systems based on the current research, operational organizational structures and associated transition procedures[15] within NOAA. The necessity to address operational forecasts requirements and related research focus areas requires sufficient infrastructure investments that include:

- Easy access to current and planned observing systems needed to address the operations and research challenges associated with the life cycle of tropical storms and hurricanes,
- increase high performance computing capacity and capability to allow for higher resolution models to be used in operations,
- institutionalize and fully fund transition of research to operations to ensure an efficient process to get demonstrated research results in modeling and observing systems and platforms into operations with sufficient operations and maintenance resources, and
- enhancements to NOAA's research infrastructure to engage and facilitate interactions with the broader science and engineering community to provide increased understanding of hurricane dynamics while using all available resources.

These infrastructure investments represent immediate steps needed to improve operational forecasts. Along with the strengthening of the infrastructure, an effort is needed to formalize the pathways leading into the operational systems (R2O) as well as a mechanism to support basic and applied research activities using the operational observing system, data assimilation, and modeling infrastructure ("O2R"). To formally highlight these pathways within the current and envisioned framework, the use of process steps are needed to facilitate and rest upon the framework. In the near-term, this will assist with the evolutionary phase that needs to bolster the transfer of ideas, implementation of improved tools and techniques. In the longer-term, the transformation to a new modeling system where benefiting the larger whole is recognized will be possible. In this fashion, these parallel evolutionary and transformational efforts will capitalize on the national science and engineering expertise to increase our understanding of these storms and further improve our forecast capabilities.

Therefore, a sustained and broad hurricane research and operational forecast initiative is required to make the best use of these capabilities and improve our understanding of and ability to predict and forecast hurricanes.

3.3 Proposed framework

As the effort to align the hurricane research and hurricane forecast improvements is fleshed out and begins to take shape the resulting framework will need to ensure the greatest return on investment across the larger community. Through ongoing efforts with the larger community fully engaged the skeleton framework proposed herein is expected to provide a foundation for building upon existing infrastructure and related activities while entraining the best practices. Features to be factored into such a framework include:

- Evolutionary and transformational research projects and related changes to the forecast systems which build upon the research results,

[15] NOAA Administrative Order 216-105: Policy on Transition of Research to Application, May 17, 2005.

- Testbeds supporting the R2O concept by aligning research, identifying pathways, and using process standards for testing to demonstrate improved results and beneficial returns on investment,

- Support for O2R, with roles and responsibilities, existing infrastructure clearly documented with the operational framework provided to accommodate transformation (fast-track) R&D, and establish mechanisms to capitalize on existing and future opportunities,

- Foster collaborations and trust through communications to pool resources and align efforts to identify and focus on key questions to be addressed; pooling our best practices and combining in a manner to gain effective alignment

- The challenges to improve hurricane intensity forecasts, to extend the lead times of hurricane track and intensity forecasts and to improve confidence of these forecasts pose issues that are larger than NOAA alone can overcome. Based on previous efforts and reported recommendations, NOAA is committed to forging alliances across the research and operation communities to focus dialogue and agreed upon respective roles and responsibilities to take the necessary actions needed to develop strategies and plans to secure the research funding.

3.3.1 Basic research

Alignment of basic research along the research focus areas identified by the operational forecasters as the most pressing research needs requires coordination. In order to integrate as part of the larger national hurricane research strategy complimentary funding strategies across the agencies is needed that elevates and relies upon the strengths inherent.

3.3.2 Accelerate the transition of applied research results into operations

With the basic research community aligning to address the priority research areas identified as critical needs to improve hurricane forecasts, the next step is to infuse promising research results into operations. Focusing attention on the priority research areas through various funding mechanisms will help to form arrangements of partnerships to create synergistic outcomes and to share costs. Existing testbeds (JHT, DTC, JCSDA) that lend important support to this O2R paradigm noted earlier can be built upon to address these critical operational needs and research focus areas for advancing the prediction of hurricanes. The gains realized through engagement, alignment and partnerships will contribute to the acceleration of the application and transition of basic research into operational forecasting.

Other than the internal infrastructure there exists some key attributes that are envisioned that will ensure the maximum return on investments with the ultimate goal to transfer beneficial hurricane research results into improving operational hurricane forecasting. Several of these key attributes include: 1) support and access of numerical modeling systems to the larger research community (DTC for example), 2) acceptance and use of earth system modeling framework and associated architecture, and 3) encouragement to involve the research community through grants and visiting scientists programs.

In the end, a national hurricane research agenda aligned and encouraged to participate within the existing operational forecast systems and involved with the future generation of operational hurricane forecast systems is foreseen as the best path forward. In order to expect success, we acknowledge the need for strengthening of the infrastructure, continued support and bolstering of testbeds and the development of coordinated and complimentary roles and responsibilities within a framework to align basic research to operational forecasting needs is a pathway to success.

3.4 Social Science Research

Through review of NOAA's programs and outlined in various reports in recent years, it has become apparent that scientific understanding of physical systems and environmental processes are critical to NOAA's doing a better job of performing its mission. The HFIP Plan as described outlines ways to improve scientific understanding of hurricanes. In order to have a better understanding of how hurricanes impact society and how NOAA can translate this scientific understanding into products to best inform decision makers and the public additional societal impacts research needs to be complete. A review of societal impacts, specific to hurricanes was completed in 2005. The report, "Social Science Research Needs for the Hurricane Forecast and Warning System", authored by Jeffrey K. Lazo, National Center for Atmospheric Research (NCAR), outlines research that can be performed to take the HFIP Plan scientific findings further, by translating these better hurricane forecasts and warnings.

The HFIP Plan acknowledges the report and the recommendations to support research on the following areas:

- Warning process
- User impacts
- Decision making, especially for Emergency Managers
- Risk quantification and perception
- Behavior response
- Evacuation processes
- Economic impacts

Appendix

HURRICANE FORECAST IMPROVEMENT PLAN (HFIP)

HFIP PORTFOLIO

The HFIP Portfolio (Figure 8) comprises three major components that describe "what" needs to be supported to meet our project goal:

I. Improve Hurricane Forecast System/Global Forecast System

II. Optimize observing systems for research and operations (modeling and direct use by forecasters)

III. Expand and improve forecaster tools and applications

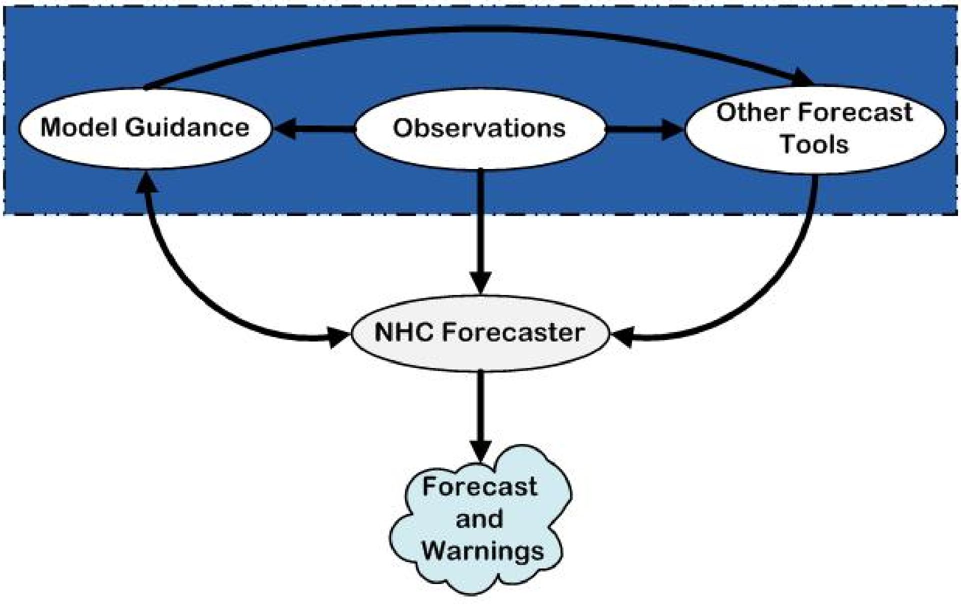


Figure 8: A simplified process of the interaction of the three HFIP components and how they contribute to the forecast and warnings delivered to the public.

Implementation Strategies: The following describe "how" the portfolio will be implemented with references to the above three components.

- Define and build an enhanced HFS/GFS capable of representing the physical processes responsible for rapid intensity change (I)

- Increase high performance computing capacity and capability to allow for higher resolution models to be used in operations (I)
- Institutionalize and fully fund transition of research to operations to ensure an efficient process to get demonstrated research results in modeling and observing systems and platforms into operations with sufficient operations and maintenance resources (I, II, III)
- Broaden and access the expertise of the operational numerical prediction and research communities and include stakeholders – this involves visiting scientists and post-docs at the NOAA operational centers, advisory committees, workshops, etc. (I, II, III)

I. Improve Hurricane Forecast System/Global Forecast System

Much of the improvement in tropical cyclone forecasting is attributed to advances in regional and global numerical prediction systems. These advances are mainly the result of: improvements in observations; data assimilation techniques; improved model physics in global forecast systems and high resolution regional models; the development of ensemble-based model guidance; and significant investments in supercomputing at operational numerical prediction centers. A technical summary of the models used operationally by NHC can be found at http://www.nhc.noaa.gov/modelsummary.shtml.

i. NOAA's Hurricane and Global Forecast Systems (see Appendices L and M of the OFCM Strategic Research Plan)

NOAA is developing a Hurricane Forecast System (HFS), defined as the Hurricane Weather Research and Forecasting (HWRF) atmospheric model system (includes Wave + Ocean + Land) to provide input to Estuary + Storm Surge models (Figure 9). The HWRF was developed at NOAA's Environmental Modeling Center (EMC) and made operational in 2007. This next generation, high-resolution hurricane prediction system is designed to address the tropical cyclone forecasting challenges of intensity, structure, track, sea state/storm surge, and precipitation. Over the next several years, currently planned HFS activities include: continuous upgrades to model physics, ongoing advancement in atmosphere and ocean data assimilation, upgrades to ocean and wave models, incremental increases in horizontal and vertical resolution (dependent on computing upgrades); and high resolution ensembles (resolution dependent on computing upgrades), coupling to an estuary and a high resolution hydrodynamic model (storm surge). In the longer term future, HWRF will make use of advanced mesoscale variational data assimilation techniques to initialize the hurricane core circulation.

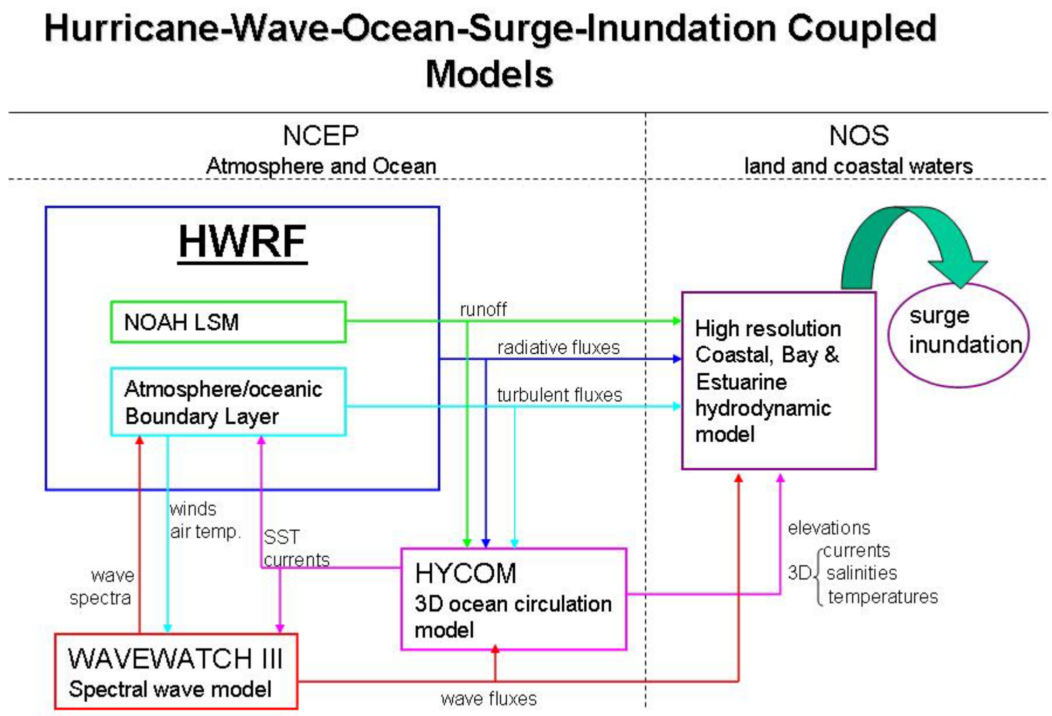


Figure 9: A flowchart describing the NOAA Hurricane Forecast System (HFS)

The Global Forecast System (GFS) technically refers to all code that supports the production of the NWS global model suite of products, including the global data assimilation system (GDAS). Developed and maintained by EMC, the GFS is a global modeling system and is typically more suited to producing genesis, track and outer wind structure forecasts (dependent on storm size). Updates to the GFS are implemented at least annually.

The capabilities of the operational modeling systems necessary to solve the issues outlined above and to achieve the required performance do not exist today and the associated challenges are presented in Table 7. The current (or soon to be[16]) operational NOAA forecast guidance systems – HFS, GFS and GFS Ensemble System along with the operational data assimilation system – run at resolutions insufficient to provide guidance at the required levels of performance to achieve the HFIP goals, particularly for rapid intensity change. Specifically, the hurricane forecast system shows very little skill at predicting intensity change with anything close to the required accuracies.

[16] Hurricane Weather Research & Forecast (HWRF) model system and data assimilation moving into operations with two nests at 27 and 9-km grid spacing using NMM core, GFS and GFDL physics:

- complete development and testing of full coupled model system
- complete development and testing of the HWRF or multi-model hurricane ensemble prediction system
- port version of HFS to DTC to make accessible to research community and to DOE for development and testing on-demand HPC computing
- complete development and testing of regional data assimilation system for tropical cyclone storm scale circulation
- complete development and implement operational storm surge modeling system

Table 7. Modeling challenges that must be addressed to improve NOAA's Hurricane Forecast Guidance:
1. Model, with a high degree of fidelity, the role of the convective processes in tropical systems and feedback with radiation -- hurricane and vortex structure, eye wall replacement cycles, scales of updrafts and downdrafts, explicit moisture processes and feedback between the convection and its environment.
2. Accurately model the energy fluxes through the air sea boundary, including the role and impact of waves and sea spray.
3. Accurately model the impact of turbulent fluxes at the convective and larger scales
4. Accurately model the energy available to the storm from the underlying ocean – to include the depth of the mixed layer and the heat transfer rates necessary to sustain and intensify the tropical system through improved ocean circulation modeling and data assimilation – this includes modeling the potential negative feedback from the storm that reduces the SST under and in the wake of the hurricane
5. Model the environmental forcing and steering from the larger scales
6. Bound the uncertainty in the forecast arising from uncertainty in the model physics and initial conditions used to initiate the hurricane forecast modeling system – HFS -- and the larger scale modeling system -- GFS
7. Address model scalability – improving overall computational efficiency

ii. Activities for Improvements to NOAA Forecast Guidance Systems

The following steps are identified to address the HFS/GFS modeling systems to accurately represent the physical processes responsible for rapid intensity change: These issues relevant to the implementation strategies include:

Develop, test, and implement:

- Near (~5 years) and long term (~10-15 years) high resolution (1 km), non-hydrostatic HFS and establish baseline performance for track, intensity, and rapid intensity change,
- Next-generation high-resolution GFS (10 km) to improve track guidance,
- HFS, GFS, and multi-model ensembles to quantify and bound uncertainty, and
- Next-generation storm surge modeling system (led by the NOAA Storm Surge Transition Project)

Research & Development Strategies for HFS/GFS:

- Research to insure the physical processes are represented accurately, and assess how these processes influence the predictability of track and intensity changes, particularly rapid intensity change,
- Research and development to enhance modeling techniques (e.g., high-resolution, data assimilation, ensembles, on-demand computing), and
- Develop and implement High Performance Computing strategy for HFS/GFS.

As we move to higher resolution models aimed at improving hurricane forecasts, it is imperative to increase computing power at operational numerical prediction modeling centers. NOAA's high performance computing (HPC) experts estimate that increasing hurricane model resolution to 1 km, with ensembles, would be on the order of 5,000 times more computationally expensive under the current forecast mode concept of operations[17] than currently available. This increase would take approximately 3 decades to achieve at current budget levels/strategies which assume processing capacity/capability grows in accordance with Moore's Law and budgets remain constant[18]. Two HPC tracks – sustained and on-demand will be developed into business cases for NOAA to increase computing capacity and capability for hurricane forecasting.

Increased Efficiency for the Transition of Research to Operations

While a research strategy for model guidance is a critical part of this plan, NOAA realizes the benefit of this research through its use in operations (forecasting). An efficient end-to-end transition process is required to get model advancements developed through research to the forecaster's desk.

This strategy builds upon NOAA's long-standing operational modeling capabilities with a new focus on building upon the observations and modeling system for research and transition to operations in order to accelerate improvements in track and intensity forecasts used by the emergency managers and other decision-makers.

Key questions to be addressed by the HFIP for success in HFS/GFS improvements:

- At 1-km or less grid resolution which physical processes are crucial to the intensity change problem and are they predictable on the time scales needed? What is the necessary vertical resolution vs. horizontal?
- What is the appropriate physics package and what complexity is essential to address the intensity change problem (e.g. atmosphere-ocean boundary layer, microphysics, radiation)
- What is the best way to determine predictability with reference to the forecast metrics? Can ensembles be used to increase the predictability and at what scales?
- What is the best way to develop ensembles for the intensity change problem, i.e., multi-models, different physics packages, different initial conditions?

Many of the identified questions will be addressed by the external research community through grants and other collaborative efforts.

II. Optimize Observing Systems for Research and Operations (modeling and direct use by forecasters)

Continuing to advance observational capabilities for tropical cyclone analysis, forecasting and numerical weather prediction is a vital component of the HFIP. There is a continuum

[17] Forecast mode concept of operation requires an approximate 3 hour window every 6 hours for GFS/HFS to run operationally. Forecast guidance out to 5 days is generated and updated every 6 hours over the lifecycle of a storm and delivered approximately 5 hours after the forecast valid time.
[18] ibid footnote 1

from exploratory scientific research, conducted with new types and new generations of advanced instruments and platforms, to the proven operational systems relied upon for routine and severe-event analysis and forecasting. Over the past four decades and more, NASA research satellites and airborne observing systems flown by DOD and NOAA have made major contributions to the operational systems.

To help meet the operational needs identified in Table 1, there are many planned observation platforms and instruments to enhance observing capabilities for tropical cyclone forecasters and tropical cyclone numerical prediction systems (Figure 10). With several new observational platforms and sensors potentially available in the next several years, *a capability is needed to evaluate the utility of observing platforms and instruments and advise NOAA on the its investment decisions* for improvements in tropical cyclone analysis, forecasting, and operational modeling.

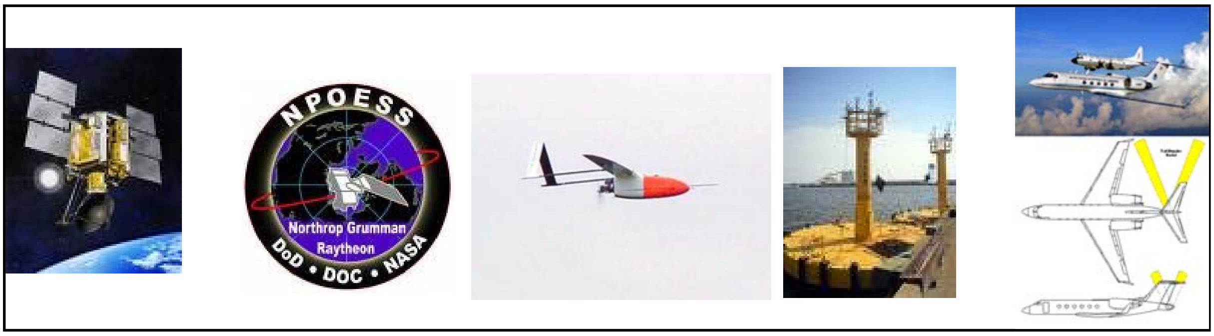


Figure 10: Examples of current and/or future observing systems and platforms that may be used for improvements in tropical cyclone analysis, forecasting and modeling. (From left to right, QuikSCAT satellite, NPOESS emblem, unmanned aircraft system (UAS), NOAA buoy, tail Doppler radar.)

Observation platforms in need of evaluation to determine their utility in improving hurricane intensity forecasts include:

- Three-dimensional wind structure from Doppler radars and lidars (airborne, ground-based, satellite-based),
- Ocean surface vector winds (e.g., QuikSCAT, Advanced Scatterometer (ASCAT), WindSAT, Next Generation Ocean Surface Vector Wind (XOSVW) mission),
- Upper ocean currents and thermodynamic structure (e.g., satellite microwave and altimetry, fixed buoys, expendable probes, drifters, gliders, and floats),
- Unmanned observing systems (e.g., UAS: both high-altitude long endurance (HALE) and low-altitude long endurance (LALE), UOV, AUV),
- Three-dimensional atmospheric thermodynamic and microphysical (hydrometeor and aerosol) structure (e.g., microwave sounders, radars, lidars, GPS dropsondes, GPS occultation, NPP, NPOESS, GOES-R).

<u>Activities to Evaluate Observing Systems to determine the optimal systems/platforms for improvements in hurricane forecasts</u>

Establishment of an observing system evaluation capability within NOAA (in coordination with the NOAA Observing System Council) is necessary to:

- Support NOAA in its investment decisions on observing systems and platforms,
- Prioritize NOAA's investments to improve hurricane observing system analysis and the forecast guidance for intensity and rapid intensity change (e.g., Observing System Experiments (OSE) and Observing System Simulation Experiments (OSSE)),
- Define research & development agenda to improve hurricane observing systems for exploratory platforms (e.g., investigation of new satellite and unmanned observing systems through partnerships with NASA and DOD),
- Demonstrate the utility of observations to improve HFS guidance, and
- Define and execute targeted field experiments to focus on key physical processes to support HFS development.

Optimize transition of observing system advances for direct use by forecasters

- Improve access to and utility of new observations for the forecasters
- Streamline process to transition new observations and platforms into operations
  – Ensure life-cycle plan provides sufficient O&M support

This strategy builds upon NOAA's long-standing hurricane research and operational observing capabilities. This plan focuses on developing a capability, together with the operational community, to evaluate the utility of existing and new observing capabilities to improve the hurricane forecast guidance.

Key questions to be addressed by the HFIP to optimize observing systems for research and operations:

- What is the best observing strategy to initialize the storm core to predict intensity change - three-dimensional winds, thermodynamics, both?
- How dense do the observations need to be in the horizontal and vertical? How often do they need to be collected? How symmetric around the storm do they have to be? How can we handle data gaps in time and space? How to characterize the magnitude of dependent variables in various regions of the vortex, and their rates of change in space and time?
- How can we improve the use of single layer observations (surface or others) to initialize the models?
- What is the best ocean observing strategy to initialize the upper ocean models (e.g., satellites, in situ, autonomous underwater vehicles (AUV))? What sustained ocean observations are necessary?
- What is the best way to address the following gaps?
  - No formal observing system analysis process presently available for the HFS,
  - Joint Center for Satellite and Data Assimilation (JCSDA) chartered for satellite observations, but not other observations, and
  - No coordination exists with IOOS for ocean observations in hurricanes

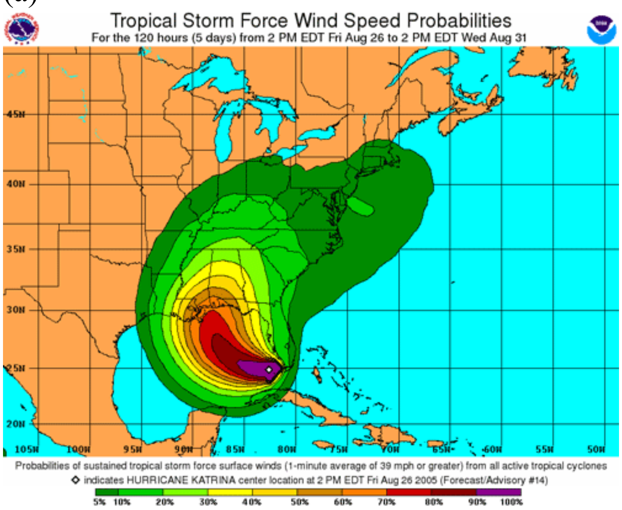
III. Expand and Improve Forecaster Tools and Applications

Forecaster tools and applications are value-added techniques (e.g. statistical approaches, display tools, historical data, and simplified models) developed outside of traditional numerical prediction models and make use of the suite of observations, model outputs, and other inputs to forecasters to help in the analysis and forecast process. Many of the new and existing tools were developed and transferred to operations through the Joint Hurricane Testbed (Figure 11).

Examples of these tools include:

- Observing tools: GPS-dropsonde, Stepped-Frequency Microwave Radiometer (SFMR), airborne Doppler radar, QuikSCAT
- Supporting applications:
  - Wind speed probabilities
  - Statistical Hurricane Intensity Prediction Scheme (SHIPS)
  - Rapid Intensity Index (RII)
  - NOAA/DOD Automated Tropical Cyclone Forecast (ATCF) system
  - NCEP Advanced Weather Interactive Processing System (NAWIPS)
- Forecast product enhancements
  - GUNA (consensus of four models) and CONU (consensus ensemble) combination schemes
  - Model confidence circles

(a)



(b)

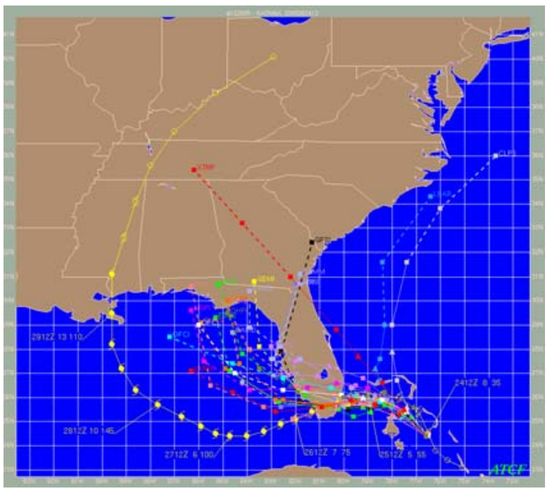


Figure 11: Examples of forecaster's tools: (a) Tropical Storm Force Wind Speed Probability graphic for Hurricane Katrina; (b) Automated Tropical Cyclone Forecast (ATCF) for Hurricane Katrina

Activities to Expand Forecaster Tools and Applications

The encouragement of innovations from the research community and pathways to develop new operational tools through a fully funded Joint Hurricane Testbed are needed to achieve desired improvements.

Many of the forecaster tools used by NHC (e.g., those mentioned above) have been a direct result of innovations from laboratories and academia through the Joint Hurricane Testbed. It is expected that a stable, fully funded JHT will provide funding to the research community to test applications in an operational setting, transition them to be evaluated internally, and implement them operationally if proven to be of value to the forecasters.

Key issues to be addressed by the HFIP for success in an expanded suite of forecaster tools:

- New sensors on a variety of platforms and development of algorithms to extract hurricane and environmental information useful to forecasters from new satellite systems
- Continued development of simplified analysis and prediction methods through the JHT as benchmarks for HFS improvements and stand-alone forecast tools
- What is the best way to address the following challenges?
    - Increase support for Joint Hurricane Testbed
    - Secure techniques developers for operations
    - Ensure the necessary computational upgrades need for transition in to operations