Background:
Note: there is a power point presentation that accompanies this document.

NOAA Science Advisory Board (SAB) established the Hurricane Intensity Research Working Group (HIRWG) to review NOAA's efforts to improve hurricane intensity prediction. 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. In result, 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 in hurricane-strength storms.

The HIRWG recommendations including: research focusing 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 response to the HIRWG report, NOAA convened a corporate hurricane summit developing unified strategy to address hurricane forecast improvements. On May 10, the NOAA Executive Council (NEC) established the NOAA Hurricane Forecast Improvement Project (HFIP), a 10-year 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.

On May 31, 2007 the project lead and deputy lead were selected, after which, a project team was formed. The HFIP Team was charged with two actions: (1) Specify stretch goals and metrics as a function of user needs and scientific understanding, and (2) Develop a balanced and prioritized project plan building on NOAA's Weather & Water Goal Team Hurricane and Related Inundation Theme Plan, OFCM Report, and HIRWG recommendations. The outcome of this plan is to ultimately enable communities and individuals to reduce the Nation's risk to hurricane impacts by delivering improved forecast guidance and tools for community planners and other decision-makers.

(1) Stretch Goals and Metrics:

The HFIP Plan defines a set aggressive metrics related to hurricane track and intensity improvements for 1, 2, 3, 4, and 5 day lead times, with a focus on rapid intensity change.

Recent research[1] notes the largest intensity forecast errors are caused by rapid intensity change. NHC has identified rapid intensification at the greatest challenge to its forecasters and rapid intensity changes are not handled well by operational models (e.g., need accurate representation of inner core and convective scale physics, model resolution, predictability, etc.). **As such, it is believed that the research and operational work necessary to improve forecasts of rapid intensity change will also serve to improve intensity and track forecasts.**

The first two HFIP metrics seek to reduce forecast errors in hurricane track and intensity for all lead times. Improved track guidance is essential for improvement of intensity forecasts, which provide better guidance to emergency managers and decision makers. More accurate information provided to emergency managers and decision makers supports planning, preparedness, and mitigation efforts.

Emergency managers at the federal, state, and local levels have varying requirements for evacuation decisions, but what is consistent beyond a desire for a perfect forecast, is the need for increased confidence in forecasts beyond 48-72 hours as the system approaches their warning area. Because of the current uncertainty in the forecast guidance for intensity and intensity change, the emergency managers are trained to anticipate at least one Saffir-Simpson category stronger storm when planning their evacuations. The impact on their plans in the event of a rapid intensification during the critical warning period before landfall could be disastrous. In order to address this critical warning issue the HFIP developed metrics specifically for rapid intensity change and uncertainty.

The next two metrics deal with the increasing the Probability of Detection (POD) and decreasing the False Alarm Ratio (FAR) of rapid intensification (RI) events. The POD describes how likely NOAA is to predict the occurrence of an RI event. The FAR is how often NOAA "cries wolf" or predict an event to occur and it does not happen. Increasing the POD and decreasing the FAR of RI events can lead to greater confidence in NHC forecasts by the users, which is a collective need of the emergency managers. The final HFIP metric further addresses that need by aiming to reduce the uncertainty in the forecast.

These new metrics are designed to insure that emergency managers and decision makers have significantly improved guidance on the possibility a storm might exceed an intensity greater than they planned for.

(2) Balanced and Prioritized Project Plan

NOAA focused the HFIP Plan on the research and development issues identified by operational needs that will lead to improved forecast guidance and tools. The following describes what NOAA needs to do to achieve the metrics and how NOAA will implement these activities:

WHAT: The major components of the HFIP Plan are to:

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[1] Ibid footnote 3

- Improve Hurricane Forecast System (HFS)[2]/Global Forecast System (GFS) to reduce error in track and intensity guidance (operational numerical weather prediction (NWP) models and data assimilation)
- Optimize observing systems to enhance capabilities for hurricane research, operational modeling, analysis and forecasting.
- Expand and enhance forecast tools and applications to add value to the model guidance and direct use of observations

HOW: The HFIP strategies to improve hurricane forecasts are based on a program of both research through strong engagement with the external community and operations coordinated to:

- Define and build an enhanced HFS/GFS capable of representing the physical processes responsible for rapid intensity change
- 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
- Broaden and access the expertise of the operational NWP modeling and research communities and include stakeholders – this involves visiting scientists and post-docs at the NOAA operational centers, advisory committees, workshops, etc.

The details of the HFIP Plan are in the attached document. Detailed responses to the HIRWG recommendations based on this Plan are included below.

Detailed Response to HIRWG:

There are two HIRWG reports: a Majority report supported by 7 of the 10 members; and a Minority report put forward by two members. The Majority report puts forward 29 recommendations on how NOAA can make dramatic improvements to intensity forecast skill in the next 5 years. Ten of the 29 recommendations, deemed critical to the success of the effort, should receive the highest priority for implementation. The Minority report made 8 recommendations, some of which overlapped with the majority report, primarily putting their emphasis on development of a simpler numerical model framework (one that combines simpler analytic models with not so high resolution numerical models), focus modeling efforts on stronger systems, laboratory experiments to test new hypotheses (e.g., air-sea interaction), and UAS observing technology.

Majority Report Recommendations:
Highest Priority:

1) (overarching) NOAA should allocate sufficient resources and provide national leadership to enable the high-priority research-and-development activities recommended below to be

[2] The HFS is currently the Hurricane Weather Research and Forecast (HWRF) coupled model and data assimilation system composed of two nests at 27 and 9-km grid spacing using the Non-hydrostatic Mesoscale Model (NMM) core, and physics from the NCEP Global Forecast System (GFS) and the Geophysical Fluid Dynamics Laboratory (GFDL) model.

undertaken at a sufficient level to ensure positive outcomes. This funding should be for a minimum of five years, and should be protected against other budgetary pressures.

NOAA agrees and obtained Hurricane supplemental funding in FY05/06, increased funding in the FY08 President's Budget and is working additional increases into FY09 Budget Planning. NOAA formed the HFIP to develop a 10-year unified NOAA plan to accelerate improvements in one to five day forecasts for hurricane track, intensity, storm surge with a priority focus on improving forecasts of rapid intensification. As recommended by the HIRWG, the HFIP calls for additional human and infrastructure resources (e.g., items such as computational power, network bandwidth, architectural/ engineering requirements, and maintenance of applicable systems) to support development, operations, and maintenance of advanced data assimilation and NWP modeling systems and other forecaster tools. The plan recognizes that 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.

2) (short term, 1-2 years) Support should be provided for development and validation of high-resolution, coupled hurricane-ocean models that incorporate appropriate atmospheric and oceanic physics representations derived from the results of recent field experiments, such as CBLAST and RAINEX.

NOAA agrees and 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. The HWRF, developed at NCEP's Environmental Modeling Center (EMC) was made operational in 2007 using a two-way moving nest with a horizontal grid resolution of 9-km on the inner nest surrounded by a 27-km horizontal grid spacing on the outer mesh. In the future, the HWRF will make use of advanced mesoscale variational data assimilation techniques to initialize the hurricane core circulation. The HFIP plan includes the development of an accelerated high resolution HFS with an inner nest horizontal grid spacing of at least 1 km running on Department of Energy (DOE) high performance computers to demonstrate the utility of such a high resolution model can better represent the physical processes important to forecasts of rapid intensity change, while maintaining a sustained development path that continues incremental improvements. The HFIP also provides support for the development of the next generation GFS to provide the required boundary conditions and environmental flow for the HFS. Over the next several years, the sustained 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), high resolution ensembles (resolution dependent on computing upgrades), coupling to an estuary, and a high resolution hydrodynamic model (storm surge).

In 2005 NOAA organized the Intensity Forecast Experiment (IFEX) as a partnership between the Hurricane Research Division (HRD), EMC, the National Hurricane Center (NHC), Aircraft Operations Center (AOC), and National Environmental Satellite Data Information Service (NESDIS). The goals of IFEX are the collection of data to directly aid the development and evaluation of the next generation operational tropical cyclone forecasting model system

(HFS/GFS). IFEX is intended to improve the prediction of hurricane intensity change by:

1) collecting observations that span the tropical cyclone (TC) lifecycle in a variety of environments;
2) developing and refining measurement technologies that provide improved real-time monitoring of TC intensity, structure, and environment; and
3) improving our understanding of the physical processes important in intensity change for a TC at all stages of its lifecycle.

Observations are collected in a variety of TCs at different stages in their lifecycle, from formation and early organization to peak intensity and subsequent landfall, decay over open water, or extratropical transition.

NOAA scientists are working closely with our partners from IFEX and other projects to use the observations collected to improve the HWRF. The HFIP Plan envisions a continuation of IFEX with annual efforts driven by operational need for data sets to drive the HFS initialization and evaluation, and more focused efforts every three years to collect enhanced observations to improve our understanding of important physical processes related to intensity change.

3) (medium term, 2-5 years) NOAA should reprioritize existing or acquire the necessary computing system capability to produce approximately 1-km-resolution hurricane forecasts.

NOAA agrees that research and development is needed to assess cost-benefit of 1 km resolution forecasts. 1-km models require a substantial investment in: observations to pick up physical processes at that scale, data assimilation improvements to make use of those observations, research and development for model physics at that scale, predictability of the relevant processes at this scale, development of models at that scale, and computing resources to run models at that scale. As a first step, NOAA is planning to obtain sufficient computational resources to run the hurricane model at 4 km in an ensemble mode in mid-term under its sustained HWRF development plan. NOAA is also working closely with the DOE to demonstrate the capability of running the high resolution HFS on their high performance computers at 1-km horizontal grid resolution. The initial demonstration is underway and a project plan will be put together as part of the HFIP. This would allow NOAA to make an informed decision on the high performance computing investments needed to meet the HFIP goals.

4) (medium term) A 4D data assimilation system for hurricane forecasting should be developed as a priority. This development should explore the advantages and disadvantages of both 4DVar and Ensemble Kalman Filter approaches to assimilating the diverse range of data that are available.

NOAA agrees that research and development is required, and increased computer processing is needed for such data assimilation. NOAA just implemented a new data assimilation system, replacing a spectral initialization system (SSI) with a grid-point scheme (GSI) as part of the HWRF/GFS systems. Currently, NOAA is investigating 4D data assimilation approaches along with other assimilation technologies (e.g. Ensemble Kalman Filters and other hybrid approaches) as part of the HWRF/GFS development plan. Continued evaluation of these different approaches, are a major priority of the HFIP plan, particularly for a high-resolution version of the HFS. The development of advanced data assimilation techniques is also key to the development of the HFIP Plan strategy to develop an optimal observing system for the HFS and next generation GFS systems. Such a system, together with the HFS and next generation GFS, are essential ingredients for any observing system sensitivity studies.

5) (short term) Airborne and surface-based radars offer the best opportunity to observe mesoscale fields in the inner core region but full realization of their potential requires real time assimilation into models. A focused program aimed at assimilating radar data into HWRF is recommended, with the goal of operational testing in 2007.

NOAA agrees and this type of effort is currently underway through a partnership between the National Weather Service (NWS, developing the data assimilation) and Office of Oceanic and Atmospheric Research (OAR, developing the quality control for the Doppler data on the aircraft) using the NOAA WP-3D Doppler radar systems. Most of the support for this effort was generated through the G-IV Tail Doppler Radar (TDR) upgrade. Additional research and development is necessary in this area and will be an aspect of the HFIP plan under the optimal observing system strategy, particularly in developing the best sampling strategies for initializing the inner core at high resolution.

6) (medium term) The strengths and weaknesses of current and past satellite observations for hurricane forecasting should be fully evaluated using Observing System Experiments (OSEs), with direct involvement from that portion of the academic community focused on operational products, and with the aim of developing a comprehensive plan in support of current initiatives and to recommend future directions.

NOAA agrees and these types of efforts are ongoing to a degree at the Joint Center for Satellite Data Assimilation (JCSDA) for satellite data sets and within OAR at HRD for flight level, dropwindsonde, and Doppler radar data sets. Additional resources are needed to develop a comprehensive observing system analysis approach using OSSE and OSEs, which is a major priority of the HFIP Plan optimal observing system strategy. It will be essential to evaluate the observational requirements for any HFS and GFS developments. A major requirement for this activity is a fully tested HFS, GFS, and data assimilation system to insure that the observing strategies result in model improvements. The HFIP Plan made the evaluation of observing systems based on their impact on hurricane forecasts a key strategy to be addressed given the large number of new satellite observing systems under development.

7) (short term) NOAA should develop a program for deploying Airborne Expendable Bathythermographs (AXBTs) to define the initial conditions for high-resolution, coupled ocean-hurricane prediction via an appropriate regional ocean data assimilation system that uses the previous model solutions as the background.

NOAA agrees and the NWS and OAR are working to improve the amount and use of upper ocean observations for assimilation into and evaluation of the HWRF and GFS systems. Based on recommendations from a HWRF Air-sea interaction workshop NOAA plans to address this issue with the implementation of the fully coupled model in FY08. The goal is to develop a requirement for the observations needed in the HWRF and GFS coupled model systems for upper ocean observations, to test observing strategies to meet the requirements, and evaluate the models. This activity is an important aspect of the optimal observing system strategy effort in the HFIP plan.

8) (short term) Priority should be given to enhanced support for research to advance understanding of phenomena related to predictability of rapid intensification and secondary eyewall phenomena. This should include investigations of core processes such as heat and momentum exchanges with the surface and across the eyewall and the impact of atmospheric and oceanic interactions.

NOAA agrees and the research and development to improve guidance on rapid intensity change is one of the major goals of the HFIP Plan. The Plan lays out two new metrics that specifically address rapid intensity change and its uncertainty. These new metrics are very ambitious and are the main drivers for the proposed strategies to develop an accelerated high-resolution HFS and the next generation GFS developments. It was clear that the resources in NOAA are not sufficient to meet this metric and that there needs to be increased support for interaction with the outside research community to achieve them. The HFIP Plan calls for such increased interaction through a number of avenues, from advisory committees, community workshops, post-docs/visiting scientists, and a grants/contracts process focused on research and development that will improve NOAA’s forecast guidance.

9) (short term) The hurricane modeling capability at HRD should be increased and improved, and coordinated interaction between NCEP, HRD, NCAR, and the broader community established, with the immediate goal of substantially enhanced exchanges of ideas, requirements, and support. This should be a two-way effort assigning priority to research satisfying operational needs.

NOAA agrees and the HFIP Plan proposes full support for the ongoing model development approach at EMC, encouraging support of the operational HFS at the Developmental Testbed Center (DTC) to make it available to the broader research community, and an expanded JHT grant process targeted at HFS model development research and development with transition into operations. As part of this strategy, HRD is planning to work closely with the DTC to support HWRF (and HFS) and to make it available to the outside research community. The goal of such a strategy would eventually lead to HRD becoming a partner in DTC to support hurricane model research. To support this HRD has hired one model developer with HWRF experience, and has plans to bring in 3-4 more support staff and one more researcher under the FY08 budget increases.

10) (short term) The Development Testbed Center (DTC) needs to be fully implemented and adequately funded for the task of testing new research models that have demonstrated potential for skillful hurricane intensity forecasts. This must include the capacity to test and transfer multi-faceted model applications to operational hurricane forecasting.

NOAA agrees and increased the DTC funding (through USWRP) in FY07 and plans to use DTC to support HWRF development through the research community. A high priority for the HFIP is to provide additional funding to the DTC to support the research community needs to explore improved HWRF (and HFS) capabilities.

Lesser Priority:

11) The planned HWRF Version 1 should be implemented in a timely manner and with the best possible features; the HIRWG considers that this implementation will necessitate enhanced human and financial resources in 2006 and in subsequent years for development of the next-generation HWRF in conjunction with the external research community.

NOAA agrees and the first version of the HWRF was made available operationally for the 2007 hurricane season. The HWRF will be supported by the DTC for research community access starting in FY08 with support from EMC and HRD.

12) NOAA should plan additional field experiments aimed at validating and improving high-resolution coupled models.

NOAA agrees and the NOAA Intensity Forecast Experiment (IFEX) is already addressing this. It was developed as a joint effort between NWS (EMC and TPC), HRD and NESDIS in 2005. See (2) above. Resources required for aircraft flight time and expendables are a major priority for the HFIP plan.

13) The 3DVar data assimilation system in HWRF is endorsed for version 1, but a key focus for version 2 should be on developing first-guess fields using mesoscale model output combined with global model output.

NOAA agrees and EMC is pursuing this goal in their current HWRF and GFS development plan. Increased funding is planned within the HFIP to support the research and development needed to improve the first guess fields for the HFS and next generation GFS.

14) Observing System Simulation Experiments (OSSEs) should be undertaken to determine the optimal configurations of observing systems for improved forecasts and as a guide to realigning and improving the current observing systems.

NOAA agrees and has such a capability at JCSDA for satellite observations, however they are not focused on the problem to address high-resolution hurricane inner core observations. The Atlantic Oceanographic and Meteorological Laboratory (AOML) and HRD are redirecting some of its resources to establish such a capability under the FY08 budget increase. As mentioned in (6) and (7) above this is a high priority for the HFIP Plan, and comprises a major component of the optimal observing system strategy.

15) The planned G-IV radar implementation is endorsed, as is the SFMR deployment on USAF C130s.

NOAA agrees and this activity is already underway. NWS, HRD, and AOC are working together to implement the SFMR on the AFRES WC-130 aircraft used for weather reconnaissance. As of the end of October 2007, six WC-130 aircraft already have operational SFMRs, and the AFRES is adding one additional SFMR-equipped aircraft per month. This effort was supported by the President's FY05 Hurricane Supplemental, which provided $10M for the AFRES. The NOAA WP-3D aircraft already have operational SFMRs, and the G-IV will add an SFMR with the Doppler radar in FY08. Additional research and development is necessary to assess the best strategy to use this instrument to support operations, and will be an aspect of the HFIP plan under the optimal observing system strategy.

16) NOAA should establish an independent committee to examine the potential role of UAS for hurricane observations. This examination should include use of OSSEs to assist objective determination of the potential impact of these observations.

NOAA agrees and established (FY05) and maintains a UAS Working Group. One of this group's current "high priorities" is a demonstration of using the Aerosonde low-latitude, long-endurance (LALE) UAS in partnership with the National Aeronautics and Space Administration (NASA) for hurricane reconnaissance. NOAA formed a UAS hurricane demonstration project in FY07 that is developing requirements for UAS observations in hurricanes. The project has already had one workshop in Starkville, MS in July 2007. As part of the requirements developed was two mission profiles for high-altitude long endurance (HALE) platforms such as those used by the Department of Defense (DOD). NASA is procuring two of these HALE platforms for research. Additional research and development is necessary to assess the best observing strategy to use these platforms and will be an aspect of the HFIP plan under the optimal observing system strategy, particularly in developing the best instrumentation and sampling strategies for initializing the inner core at high resolution.

17) A demonstration program should be instituted in 2006 to assess the ability of a swarm of LALE UAS to provide low-altitude in-situ observations in a critical region where manned aircraft satellite observations are lacking.

NOAA agrees and this type of demonstration program was established in 2006 for operations out of Key West Naval Air Station (NAS) for the month of September through interactions between HRD, NASA and Aerosonde, with the support of the NOAA UAS Working Group. Unfortunately, the weather did not cooperate, and the Federal Aviation Administration (FAA) delayed issuing a Certificate of Authorization (COA) to operate the Aerosonde in U.S. Air Space from Key West. However, NOAA received the COA in November 2006, which extended for one year to December 2007. HRD partnered with NASA on a similar demonstration project in 2007 from 27 August through the middle of November from the Key West NAS. To date there have been no flight opportunities. NOAA plans to extend the COA to operate out of Key West next year, and to establish an international base of operations to increase the likelihood for opportunities to fly.

18) To conduct OSSEs to determine optimal ocean observing systems in the Gulf of Mexico and in the western Atlantic, noting that these may be different.

NOAA agrees and as mentioned in (7) above, this is a high priority for the HFIP plan and will likely comprise a major component of HFIP Plan optimal observing strategy.

19) To assimilate all available radar data, including aircraft (P3, GIV) and land based (WSR-88D; TDWR and other FAA radars; TV station radars) and use this as an input to the mesoscale modeling system. Further, to conduct OSSEs to determine optimal configurations for land-based radar systems, especially around the Gulf of Mexico, in support of the mesoscale modeling effort.

NOAA agrees and is currently planning to assimilate these data into the HWRF. Increased resources are needed to implement this effort in a more timely manner. As mentioned in (6) and (7) above this is a high priority for the HFIP plan and will likely comprise a major component of the HFIP Plan optimal observing strategy.

20) Consideration should be given to developing an operational capability to generate ensemble forecasts of the hurricane intensity and to combine these in an optimum manner to provide uncertainty estimates.

NOAA agrees and is planning to implement an HWRF ensemble system, but increased resources are needed to implement this effort in a more timely manner. Additional research and development on ensemble approaches to improve forecast of track, intensity and rapid intensity change is a high priority for the HFIP plan.

21) The Developmental Testbed Center and Joint Hurricane Testbed should be tasked with improving links between NOAA operational efforts and the wider research community. These links should include evaluations of and intercomparisons between NOAA models and community models, together with the establishment of enhanced visitor and post-doctoral programs.

NOAA agrees. DTC funding was increased in FY07 to support HWRF. Additional resources could support a wider research community effort. As mentioned in (9), (10) and (11) above this is a high priority for the HFIP Plan in effort to increase interaction with the broader research community. The HFIP Plan recognizes that transition of research to operations requires robust interaction between the research and operational community, as well as a strong interface with the user community. It also requires a healthy infrastructure for the transition, processes for demonstration, operational implementation and operations and maintenance. Any weak link in these activities will be an impediment for an efficient transition. This HFIP strategy is imperative to realize any benefits of targeted research in operations. The actions are as follows:

Establish research to operations activities for Joint Hurricane Testbed (JHT) as part of base-funded operations and fully fund research to operations (R2O) needed to improve hurricane forecasts:

- Establish a full-time transition to operations staff
- Develop a portfolio of binding commitments (via JHT Charter improvements, below) defining operational needs, research deliverables, and plans for sustained operations and maintenance associated with incorporation of the enhanced operational capabilities.
- Support JHT infrastructure
- Establish IT/Modeling staff for project implementation at EMC
- Establish operations and maintenance infrastructure (staff, data flow, data management, data archival, display functions, and upgrades at NHC, EMC, and NCO)

Broaden the JHT charter and increase support to put more emphasis on HFS R&D issues, including:

- R&D for specific HFS improvements (including 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 DTC and JCSDA to address HFS issues

22) JHT funding should be restored to previous level or higher if a significant number of well-qualified proposals continue to be declined for lack of funds for these critical projects.

NOAA agrees. Since 2002 the JHT has been funded through USWRP. Additional resources are required to base fund this effort on a permanent basis. The HFIP plan places transition of research to operations as a very high priority (see previous recommendations for details), and supports a fully funding JHT, as well as DTC to promote this type of interaction.

23) Research and development aimed at improving hurricane intensity forecasting should adopt a multidisciplinary approach that includes scientific, engineering and social considerations.

NOAA agrees, however, while this is likely where NOAA will move in the future, the highest priority for the HFIP Plan is to make the modeling and observing systems useful for assessing impacts of different approaches on the forecast guidance, and transitioning them into operations. Research and development to provide support for engineering and social considerations to improve the forecast process are likely better dealt with outside of the HFIP Plan through other NOAA efforts, activities under the auspices of the Office of the Federal Coordinator for Meteorological Services (OFCM), or the National Science Board proposed National Hurricane Research Initiative (NHRI).

24) NOAA should explore possibilities, options and benefits from using the high-resolution model outputs to provide direct "impact" products as opposed to simple warnings about intensity. This could provide a valuable transition from the Saffir-Simpson approach.

NOAA agrees and is moving toward to a warn-on-impact forecast system. It makes sense that the hurricane forecast system move along with the NOAA approach. This approach is being led through the WFOs and should be driven by their requirements. There is already research underway to investigate new ways to measure hurricane impacts that are being tested (i.e., Powell and Reinhold 2007[3] work on developing new metrics for wind and surge impacts in BAMS). While not explicitly discussed in the HFIP Plan, the R&D to address this topic could easily be supported within the HFIP Plan under the expanded forecast tools and applications strategy.

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[3] Powell, M. D., and T. A. Reinhold, 2007: Tropical Cyclone Destructive Potential by Integrated Kinetic Energy, Bull. Amer. Met. Soc., 88, 513-526

25) Researchers are encouraged to develop and test reduced models and statistical techniques with operational data streams and, if successful, seek Joint Hurricane Testbed funding to transition the model to NHC

NOAA agrees and already supports these types of transition of statistical models. A number of transitions are already complete or underway and has been supported in nearly every funding cycle by the JHT since it was formed in 2002. Good examples are the Statistical Hurricane Intensity Prediction Scheme (SHIPS) model improvements, the development of the rapid intensity (RI) index, and the Logistic Growth Equation (LGE) model development. The R&D to address this topic fits within the HFIP Plan under the expanded forecast tools and applications strategy.

26) An archival system should be created that makes these important datasets readily available to the research community

NOAA agrees and this is a high priority for the HFIP Plan under the increased support for the operational model systems through the DTC and the JHT (see 10, 21, and 22). Important data sets need to be made available to all developers as a means of evaluating any model improvement slated for transition to operations.

27) The traditional verification based on track and maximum intensity should be retained for continuity, but needs to be extended by new, more comprehensive verifications, including the use of archival data, that can fully indicate the quality of intensity and structure forecasts.

NOAA agrees and there is already research underway to investigate new ways to measure hurricane impacts that are being tested (i.e., Powell and Reinhold 2007[4] work on developing new metrics for wind and surge impacts in BAMS). The R&D to address this topic for the HFS and GFS developments fits within the HFIP Plan under the expanded forecast tools and applications strategy.

28) The Saffir-Simpson categorization should be retained but be restricted to maximum winds, with removal of formulaic references to ocean and surge conditions.

NOAA agrees and there is already research underway to investigate new ways to measure hurricane impacts that are being tested (i.e., Powell and Reinhold 2007[5] work on developing new metrics for wind and surge impacts in BAMS). The R&D to address this topic fits within the HFIP Plan under the expanded forecast tools and applications strategy.

29) A more complete suite of information should be developed for use by knowledgeable audiences, including the analyzed or forecast maximum wind, overall structure (wind and rain distributions) and storm surge and ocean-wave structure, and the uncertainty in these quantities.

[4] ibid
[5] ibid

NOAA agrees and this is a priority for the HFIP plan, particularly in assessing model, data assimilation, and observations strategy impacts. The R&D to address this topic fits within the HFIP Plan under the expanded forecast tools and applications strategy.

Minority Report recommendations:

1) NOAA should develop a procedure for coupling existing mesoscale numerical models in the outer regions of a tropical cyclone with simpler numerical/analytical predictive tools developed specifically to describe the inner core and boundary-layer regions, with a view to employing these models in operational forecasts.

NOAA sees potential benefits to this recommendation, however, it is not explicitly discussed in the HFIP Plan. The R&D to address this topic could easily be supported within the HFIP Plan under the expanded forecast tools and applications strategy.

2) NOAA should continue to focus resources allocated for operational hurricane intensity forecasting, and for research targeted to upgrade that forecasting, tightly on hurricane-like systems, especially higher-speed vortices closer to landfall.

NOAA agrees and the HFIP Plan targets the probability of detection and the false alarm ratio of storms that undergo rapid intensity change over 24-h at all lead times prior to landfall as an objective. In doing so research is needed on what approaches will yield the best forecast performance. The R&D to address this topic fits within the HFIP Plan under the expanded forecast tools and applications strategy.

3) NOAA should avoid the use of very high-resolution numerical models, substituting simpler analytic/numerical methods to represent critical smaller-scale phenomena. NOAA should also tentatively proceed with hurricane-intensity-forecast models not incorporating sea/air coupling or use simple models to represent the coupling, especially since the key sea/air transfer formulae will remain largely empirical.

NOAA does not support this recommendation. NOAA and the larger hurricane research community (e.g. USWRP PDT-5 report, NSB report, HRWG majority report, and OFCM Federal plan for hurricane research "The Way Ahead") expects that the biggest gains in our ability to forecast hurricane intensity and structure will come from improved numerical weather prediction models. The consensus of these reports and the Majority recommendation was that the high-resolution numerical model concept to improve hurricane intensity forecast guidance, especially for rapid intensity change must be evaluated. Providing a demonstration of the utility of such a model concept, and to address predictability issues raised in minority report is the basis of the HFIP Plan's strategy for development of the high-resolution HFS.

4) NOAA ought to execute, efficiently in real time, useful estimation of the "secondary effects" of a landfalling tropical cyclone, by adopting a model for each secondary effect that is accurate and simplistic, and by using a compact representation of the low-level wind field and pressure field of the landfalling vortex.

NOAA agrees that this is an appropriate area for research and development within the HFIP Plan. See response to (23) above related to the development of a warn-on-impact approach to hurricane impacts. While not explicitly discussed in the HFIP Plan, the R&D to address this topic could easily be supported within the HFIP Plan under the expanded forecast tools and applications strategy.

5) Owing to intensive investment through resources of the Department of Defense, the use of Unmanned Aeronautical Systems (UASs) for the remote sensing of hurricanes is deemed of high promise. NOAA should form an internal study group for the transfer and deployment of high-performance UASs as they become available from the US Military. This study should include determination of proper instrumentation, site selection, and crew training, with a view to achieving operational status within 3-5 years.

NOAA agrees and is already supporting the concept of using UAS in hurricane research and operations. NOAA maintains a UAS Working Group. See reply to Majority recommendations (16) and (17).

6) NOAA should adopt a general policy of requiring the integration of laboratory scale experimentation with every "field"-experiment initiative as a lower-cost way of evolving tentative theses, to be confirmed, modified, or rejected in subsequent at-sea testing.

NOAA recognizes the potential benefits to these recommendations, however this is an activity more appropriate for the basic research community working closely with NOAA applied research. Some of this work is already underway at the University of Miami (RSMAS) with the same tank and also onboard the NOAA P-3 aircraft, partially funded by NOAA and Office of Naval Research (ONR, Drennan is the PI). The work continues and has led to a manuscript in review. This research and development is more basic than envisioned within the HFIP Plan, and are likely better dealt with outside of the HFIP Plan through other NOAA efforts, activities under the auspices of the Office of the Federal Coordinator for Meteorological Services (OFCM), or the National Science Board proposed National Hurricane Research Initiative (NHRI).

7) Measurements by Mark Donelan and his associates in a combination wind tunnel and programmable wave tank (with subsequent support from data taken at sea as part of the CBLAST project), show that the drag coefficient at the air/sea interface does not continue to increase with the atmospheric-wind speed for storm-force and higher winds. These experiments in the laboratory ought to be extended to encompass heat and mass transfer from slightly warmed water to moist air flowing above, to resolve the long-standing uncertainty about how the turbulent exchange coefficients for temperature and moisture vary with wind speed. The potential uses for a suitably instrumented wind-wave tank include the furnishing of a vast amount of data about the nature of an air boundary layer evolving over a sheared layer of water. Moreover, NOAA should convene a study group to produce concrete recommendations about a feasible design for a circular wind driven wave tank of order 20-m diameter, to create a swirling flow boundary layer over a warm water pool (a laboratory simulation of the very-low-level flow in a hurricane).

NOAA recognizes the potential benefit of these recommendations, however, this is an activity more appropriate for the basic research community working closely with NOAA applied research. Some of this work is already underway at UM/RSMAS with the same tank and also onboard the NOAA P-3 aircraft, partially funded by NOAA and ONR (Drennan is the PI). The work continues and has led to a manuscript in review. This research and development is more basic than envisioned within the HFIP Plan, and are likely better dealt with outside of the HFIP Plan through other NOAA efforts, activities under the auspices of the Office of the Federal Coordinator for Meteorological Services (OFCM), or the National Science Board proposed National Hurricane Research Initiative (NHRI).

8) A National Hurricane Research Laboratory should be established (more accurately, restored) at a single location in Miami, with responsibility for all hurricane-related research, including analysis, numerical modeling, instrumentation, and large-scale laboratory experiments. Organizational units currently located elsewhere that fit into the NHRL should be relocated. The NHRL should be located as close to the operational hurricane forecast group (NHC) as possible. It should be endowed with resources to hire a professional staff capable of supporting these activities, as well as host academic researchers and long-stay visitors from other NOAA laboratories on a regular basis. In recruiting the staff for NHRL, NOAA is advised to contact applied physicists, mechanical engineers, and others from the broader fluid dynamics community.

While this recommendation has merit, NOAA is addressing this recommendation outside of HFIP Plan.