Preliminary Report

National Oceanic and Atmospheric Administration

Science Advisory Board

Hurricane Intensity Research Working Group

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1 Executive Summary

1.1 Key Recommendations

Our recommended goal is:

To reduce the error in 48-hour intensity forecasts by at least 10 kt (approximately one half of a Saffir-Simpson category) within the next five years, with an emphasis on improved forecasting of rapid intensification and decay.

Achieving this goal will require support for the following key recommendations, together with adoption of the more general recommendations contained in the body of this report and summarized in Appendix 5. These key recommendations have been selected as both being compatible with current activities and providing the best potential for improved understanding and forecasting of hurricane intensity and structure, including:

- Attaining Critical Mass;
- Improving Observations of Hurricane Structure;
- Improving Data Assimilation;
- Adopting High-Core-Resolution, Coupled Air-Sea-Land Mesoscale Modeling and Analysis;
- Enhanced Work in Operations Research and Socio-Economic Impacts;
- Accelerating Transfer from Research to Operations.

1.1.1 Attaining Critical Mass and Enhancing Research/Operations Partnerships

Many participants are contributing to research and development that can impact hurricane-intensity forecasting. Taken in total, this effort represents a very resourceful pool of expertise and capability. Mesoscale modeling with high resolution in the vortex core and boundary layer is seen particularly as key to achieving our goal. Yet, with the redirection of GFDL, limited development/implementation staff at NCEP, and lack of modeling capability at HRD, NOAA currently has limited resources for both in-house hurricane-related mesoscale-model development, and interfacing with the wider research community. Excellent work is being done in the academic community and at NCAR that complements the NCEP expertise, but the coordination between this research and operational developments is deficient, and should be substantially improved.

Our specific recommendations are:

- **Short-term:** Establish a "NOAA Hurricane Team" to provide better in-house focus (NCEP/NHC, OAR/AOML/HRD), and appoint a standing SAB working group (with staggered term limits) on hurricane research to advise this Team.
- **Short-term:** A computationally practical version of the H-WRF should be implemented in the near future; this implementation probably would necessitate an enhanced effort and funding, together with better connections to the external research community.
- **Short-term:** Increase the hurricane modeling capability at HRD, and establish a partnership among NCEP, HRD, NCAR and the broader community, with the immediate goal of substantially enhanced exchanges of ideas, methodologies and support**.**
- **Short-term:** Conduct an evaluation and intercomparison of in-house models with published externally developed models; enhance visitor and post-doctoral programs, task the Developmental Test Center and Joint Hurricane Testbed project to link in-house efforts with the wider community; assist establishment of a cooperative institute dedicated to hurricanes.
- **Medium-term:** Re-establish a hurricane R&D center of excellence, in proximity to NHC, encompassing the HRD, JHT, DTC, and tropical-cyclone-related activities of the NCEP; this action essentially restores a National Hurricane Research Laboratory.
- **Medium-term:** Develop cooperative efforts with other government agencies, universities, and the private sector in areas relevant for improving hurricane forecasting, warning and community response.

1.1.2 Improving Observations of Hurricane Structure

There are numerous observing systems already in use for monitoring hurricanes, each with its own characteristics and drawbacks. Combining a broad range of observing techniques provides the best overall observing capacity. The current mix of satellites, manned aircraft, buoys, radar, etc, should be maintained as a critical component of the overall hurricane forecasting process. In addition, there are promising new technologies in-hand (SFMR) and on the horizon (UAS, radar on the G-4).

The HIRWG was concerned to learn of potential delays in important satellite initiatives, including NPOESS and the TRMM replacement, and notes that these are important hurricane-observing platforms. Our specific recommendations are:

- **Short-term:** "Low and Slow" Unmanned Aircraft Systems (UAS) have demonstrated a capacity to operate in hurricane conditions last season. A demonstration program should be instituted in 2006 to assess their ability to provide low-altitude *in situ* observations in the ocean-contiguous portion of a tropical cyclone where manned-aircraft and satellite observations are lacking.

- **Medium-term:** 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 assets, including consideration of both low-level and high-flying UAS and their optimal mix with current manned aircraft systems.

1.1.3 Improving Data Assimilation

A state-of-the-science data-assimilation system is crucial to obtaining value from nontraditional observations, such as radar, aircraft, satellite, dropsonde, etc. Evidence before the HIRWG also has emphasized that using bogus vortices to initialize the hurricane core has produced many uncertainties on intensity forecasting due to the constrained size and structure of the vortex (Xiao et al. 2000; Pu and Braun 2001; Park and Zou 2004). We recommend a coordinated program among NOAA, NCAR and academia aimed at developing an optimized data-assimilation system for hurricane models:

- **Short-term:** Include a 3DVar data-assimilation system in HWRF for 2007 and explore developing first-guess fields using mesoscale-model output as an alternative to global-model output.
- **Short-term:** Airborne and surface-based radars offer the best opportunity to observe mesoscale fields in the hurricane-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.
- **Medium-term:** Develop a 4D data-assimilation system for hurricane forecasting. This development should explore the advantages and disadvantages of both 4DVar and Ensemble Kalman Filter approaches to assimilating, in real time with available computer resources, the diverse range of data that are available.

1.1.4 Moving to High-Core-Resolution, Coupled Air-Sea-Land Mesoscale Modeling and Analysis

The HIRWG was presented with very strong evidence that models must have resolution approaching 1 km to capture phenomena in the core region that are important to accurate prediction of intensity, including eye-wall cycles. An interactive coupling between the ocean and atmosphere may also be critical. Data sets have been collected in recent campaigns that are well suited to testing and developing a high-resolution modeling capacity. Specific recommendations are:

- **Short-term:** Support upgrading high-resolution core and boundary-layer modeling through use of recent field experiments such as CBLAST and RAINEX.
- **Medium-term:** Encourage additional field experiments for validating high-resolution core and boundary-layer coupled models, and assess observing-system configurations developed from OSSEs;

- **Medium-term:** NOAA should acquire the capability to produce 1-km-core-resolution hurricane forecasts, especially for storms that are likely to affect the US within 5 days. This goal should be pursued even if it is not attainable on a 5-year time scale.

1.1.5 Enhanced Work in Operations Research and Socio-Economic Impacts

Whilst improved intensity and structure forecasting is the primary focus of this report, evidence presented to the HIRWG indicated considerable gains by coupling research with better understanding of how forecasters apply new information, and also of how direct forecasts of impacts could improve the overall warning effort:

- **Short-term:** Develop an understanding of how forecasters and other users will apply improved intensity predictions to decision making, and use this to design intensity products and services. A component of this research should be the exploration of results from improved track forecasting;
- **Medium-term:** Explore possibilities, options and benefits from providing direct "impact" products, as opposed to simple warnings about intensity.

2 Introduction

2.1 Motivation for this Report

Research and development has resulted in substantial improvements over the last two decades in forecasting of hurricane track (Fig. 1). But improvements have not been achieved in intensity and structure forecasting. In particular, rapid intensification and decay are poorly forecast and this leads to overly precautious warning, with its economic consequences, and reduced willingness by the public to take action when a real threat emerges. For example, recent “surprises” have included:

- Charley – 2004 – rapid strengthening just before landfall
- Katrina – 2005 – rapid weakening just before landfall
- Wilma – 2005 – rapid strengthening to record low central pressure

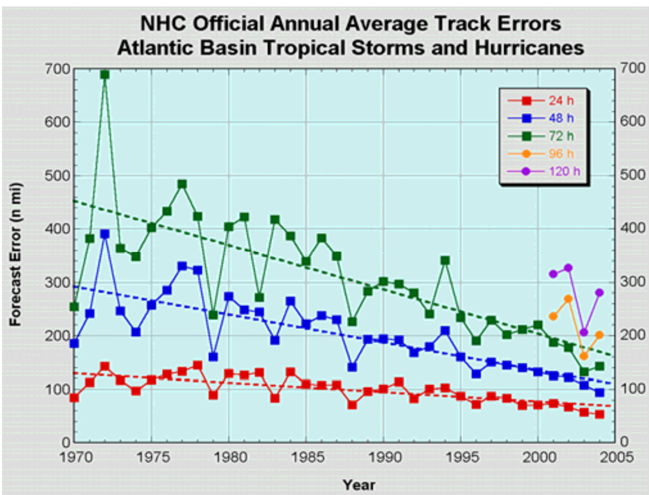


Figure 1: a) Improvements in annual track errors since 1970, and b) Lack of improvement in annual intensity errors (to be added).

The HIRWG was constituted to address this lack of progress, with a specific charge to:

- Independently assess the current “state of the science” and R&D activities in NOAA and elsewhere with respect to hurricane intensity; and then
- Recommend an agenda of R&D activities that will lead to an improved understanding of the processes determining hurricane intensity and the timely transfer of that understanding to operations.

The full terms of reference appear in Appendix 1, and the membership of the HIRWG appears in Appendix 2.

2.2 Focus of the Report

The report focuses on the application of science to improve operational forecasting of hurricane intensity and related structure. This includes specific recommendations on:

- Application of current knowledge to this forecast problem (primarily a development question);
- Identifying techniques that should receive priority attention, such as high-rsolution numerical modeling (primarily a technique-development agenda); and,
- Identifying phenomena toward which additional research should be targeted (primarily an applied-research agenda).

2.3 Definitions

A full set of acronyms and definitions is provided in Appendix 3. Specifically, we define:

- *Research* as seeking new knowledge and understanding about nature, including the development of specialized tools and techniques for such purposes;
- *Development* as converting existing scientific knowledge, tools, and techniques into operational tools and techniques that produce improved products and services;
- *Short term* as1 to 2 years - having potential for impact in the 2007 hurricane season if activity started in Fall 2006, but with little impact on budget process;
- *Medium term* as 2-5 years - having potential for impact in the 2009 hurricane season and does impact future budgets;
- *Long term* as > 5 years – having potential for impact but this time frame is outside the primary scope of this report.

2.4 Organization of the Report

The report is organized along the following lines:

- A statement of the overall problem and challenge of intensity and structure forecasting is presented in Section 3. This includes discussion on the increasing risk and vulnerability, communicating the impacts, the state of the science and key research areas to address forecast needs;
- The key observing components are addressed in Section 4. This covers the use of Observing System Simulation Experiments (OSSEs) for determining the best mix of observations, together with the major observing systems: Satellite, Manned Aircraft, UAS, Surface, Land-based Radar, and Balloons and Rawinsondes;
- Section 5 addresses numerical modeling aspects, with a discussion of current operational and research models, the need for advanced high-resolution modeling, data assimilation, potential contributions from simple model systems and statistical techniques, derived products, and related computing issues;
- Short, medium and long-term research recommendations are presented in Section 6, together with a discussion on moving from research to operations;

- Finally, salient details on the terms of reference, HIRWG membership, timeline, presentations to the HIRWGm definitions and terms, and a summary of recommendations are presented in Appendices 1-6.

3 Statement of the Problem – The Challenge of Forecasting Tropical Storm and Hurricane Intensity and Structure

3.1 Definition of Intensity

We adopt the NHC definition of intensity as being the maximum 1-minute-sustained 10-m-height winds in the core of the storm. However, we note that this variable is rarely, if ever, directly measured, and is normally inferred by extrapolation from ground or aircraft observations by satellite pattern-recognition techniques, or by pressure-deficit/maximum-wind relationships. The conversion for classification of tropical systems in the US is:

- Tropical Depression: loosely defined as a warm-core closed circulation with deep convection, but generally has maximum winds between 25 and 34 kt;
- Tropical Storm: maximum winds between 35 and 63 kt;
- Hurricane: maximum winds greater than 63 kt.

Hurricane intensities are further subdivided into five categories known as the Saffir-Simpson scale:

- Category 1: maximum winds 64-82 kt with storm surge of 4-5 ft
- Category 2: maximum winds 83-95 kt with storm surge of 6-8 ft
- Category 3: maximum winds 96-112 kt with storm surge of 9-12 ft
- Category 4: maximum winds 113-135 kt with storm surge of 13-18 ft
- Category 5: maximum winds >135 kt with storm surge of >18 ft

The broad categorization of the Saffir-Simpson scale provides a robust and easily understood way of communicating the potential impact of a hurricane, and is consistent with the current uncertainty in both track and intensity forecasts. It is well understood by vulnerable communities; emergency-management decisions are based on this scale at the local level; and it has been adopted around the world (in slightly different forms). The HIRWG was presented with weaknesses of the approach, particularly (1) the possible perception that a major difference attends a change in category which in fact may be occasioned by only a small change in actual intensity, and (2) the poor real relationship between category and storm surge (which depends on the total wind structure, direction of storm approach to the coast, storm size, coastal configuration, bathymetry, and parameters other than the maximum wind). However, we consider the advantages outweigh the deficiencies, and the scale should be retained in its present form, but with a focus on wind speed only. Wave height and storm surge should be handled separately.

We also note that the present strong focus on intensity does not adequately communicate the total threat, which comes from a combination of maximum winds, wind structure (including size and asymmetry), the accompanying wave and surge characteristics, the rainfall structure, and sometimes tornadogenesis. We therefore recommend that a more complete information package be developed for use by more knowledgeable audiences, including the analyzed or forecast maximum wind, overall structure (wind and rain) and storm surge and ocean-wave structure. This information would best be portrayed in a simple and easily understood graphical form.

Recommendation: The Saffir-Simpson categorization should be retained, but be restricted to winds, with removal of formulaic references to ocean and surge conditions, and be supplemented by a more circumstantial, graphical description of the important storm parameters such as wind structure, surge and rain distribution. The value of the peak sustained-wind speed and an estimate of the uncertainty should also be provided.

3.2 Increasing Risk and Vulnerability

The last decade in the North Atlantic has seen hurricane activity and intensity at record levels. There is vigorous debate on the relative contributions of natural cycles and greenhouse warming to this active period. However, both sides are in agreement that the current high level of activity will not diminish in the near future. Further, there is evidence that the most effected regions will be Florida and the Gulf states (G. Holland, personal communication (pc), 2006), which recent events have shown to be highly vulnerable to cyclone impacts. Coupled with these climatological changes has been a very large increase in populations, industry and commerce in vulnerable coastal regions (Pielke et al, ****).

This combination of increasing risk and vulnerability requires a careful and well-funded approach to improving the forecasts and warnings, communicating this information and developing appropriate response strategies.

3.3 Communicating the Hurricane Risk

The primary goal of hurricane forecasting is to provide a prediction of the impacts a hurricane will have, with sufficient lead time to enable adequate responses to be taken. Such responses include effective decisions on, and enactment of, community responses to secure buildings and valuables, evacuate the threatened area, shut down industry, and, for emergency managers, to prepare for the post-landfall response. The time scales for such responses vary from as long as 120 hours for the military and some industries, to 36-48 hours for local evacuations. The track forecast is most important at the longer time scales, and intensity becomes important within around 48 hours (NOAA watches are issued for the next 36 hr, and warnings for the next 24 hr). A major concern that has been communicated by a number of groups is the danger of rapid intensity change just before landfall, when adequate response can no longer be taken.

We emphasize that there is a considerable difference between *forecasting, warning* and *response*:

- Forecasting is the real-time projection of the relevant meteorological and oceanic parameters and is an applied-science problem, which is best addressed by advanced research and by development of practical technical tools for prediction, such as numerical models and statistical techniques;
- Warning is a social problem, which requires understanding of difficult-to-define parameters such as vulnerability and risk, and assessment of the impacts of uncertainties in the forecast process;
- Response is partly a social and partly an engineering problem, which involves an understanding of the adequacy of the infrastructure to withstand the hurricane onslaught, the sophistication of the community and its capacity to respond, and effective communication and logistical approaches.

Thus, appropriate community response means that effective research and development aimed at improving intensity forecasting must involve a multidisciplinary combination of scientific, engineering and social considerations. The science should be responsive to the major social and engineering needs and the social and engineering approaches should take adequate account of the inherent limitations of the scientific components of the problem.

A major consideration for such research and development should be how to communicate effectively the inherent uncertainties. This is acknowledged to be a difficult problem. Purely deterministic forecasts are clear and unambiguous, but they omit important information on the potential range of risk. Conversely, probabilistic methods are often misinterpreted, even by relatively sophisticated users.

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

3.4 Status of Intensity Understanding and Forecasting

As is recognized by NOAA's formation of the HIRWG, there are substantial deficiencies in both our knowledge and forecasting of hurricane intensity and structure. However there have been significant advances in knowledge over the past couple of decades, including:

- Improved specification of how sea/air transfer varies with the near-surface wind speed (Chen et al. 2004; more references);
- Recognition of internal processes, such as eyewall vortices, secondary eyewalls and eyewall-replacement cycles (Zhu and Zhang 2004, Willoughby et al. 1982);
- Understanding of the oceanic response to the hurricane passage (Bender et al. 1993, Shay et al. 1998, Jacob et al. 2000);

- Improved knowledge and specification of the mechanisms by which energy and momentum are transferred to and from the underlying surface (Emanuel reference, Holland 1995, Chen 2005); and,
- Description of the potential impacts of the near environment, including upper troughs and interactions with nearby weather systems (Molinari ***, Bosart ***)

But there still remain great uncertainties in our understanding, and the above-cited advances in knowledge have not been translated into improved forecasts.

Current forecast skill is not adequate for effective warning, and this shortcoming can be traced directly to the deficient guidance that is available to the NHC forecasters (Lambert et al. 2006). The skill of these guidance products is largely due to simple statistical and climatological techniques, none are able to consistently forecast rapid changes of intensity, and the level of skill has barely increased in the past decade. The 48-hour forecasts of maximum intensity (time of greatest potential damage) are *consistently* 20 kt (one Saffir-Simpson category) too low, a discrepancy which far exceeds the National Weather Service objective. A result of emergency managers consistently preparing for storms that are often one category worse than forecast often leads to an unnecessary response that is costly, and reduces public confidence and willingness to react to genuine danger.

The HIRWG fully concurs with the assessment by Max Mayfield, Director of the NHC, that the highest-priority requirement is for improved guidance products to help the NHC forecasters to predict rapid intensity increases and decays.

The current lack of accurate forecast guidance can be attributed to a range of causes:

- Lack of understanding (and observations) of the atmospheric and ocean processes that lead to tropical-cyclone intensity increases and decays. These intensity-change processes are complex, and because the critical changes occur in the region of the high winds and waves, they are very difficult to observe;
- Inadequate intensity-forecast systems. Whilst there have been modest advances in statistical forecast approaches and helpful combinations of numerical model forecasts (the super-ensemble), current numerical guidance is an excellent supporter for track prediction but has little or no real skill at forecasting either intensity or structure; and
- Inadequate assimilation of current observations into the forecast process.

The current situation has some similarity to that for hurricane track forecasting twenty years ago. Then, a well-funded and focused research and observational program, combined with development of relevant numerical guidance products, has contributed to reducing the track-forecast errors substantially; current 72 h errors are approaching those of 24 h in the 1980s. These improvements raise hope for similar improvements resulting form focused efforts dedicated to upgrading intensity forecasting, although predicting track is much more dependent on the atmosphere around the vortex, while predicting intensity also depends very much on the internal details of the vortex. Some noteworthy recent undertakings are:

- Research forecasts with high-resolution numerical models have shown skill at both resolving and reconstructing core and near-core features, such as eyewall cycles, overall wind structure, and rainfall structure (S-Y. Chen, pc 2006; G. Holland, pc 2006);
- Field experiments such as the NASA/NOAA Convection and Mesoscale Experiments (CAMEX), the Office of Naval Research/NOAA Coupled Boundary Layer Air-Sea Transfer (CBLAST), and the NSF RAINband Experiment (RAINEX) have produced yet-to-be-analyzed data sets, including observations in intense hurricanes. These data provide a possible basis for both improved understanding and testing future forecast techniques.

3.5 Key Research Issues to Address Forecast Needs

The HIRWG regards research and development, conducted in a coordinated manner, with a well defined national leadership, as providing considerable promise for future improvements in intensity forecasting. A schematic of activities leading to working operational products is shown in Fig. 2.

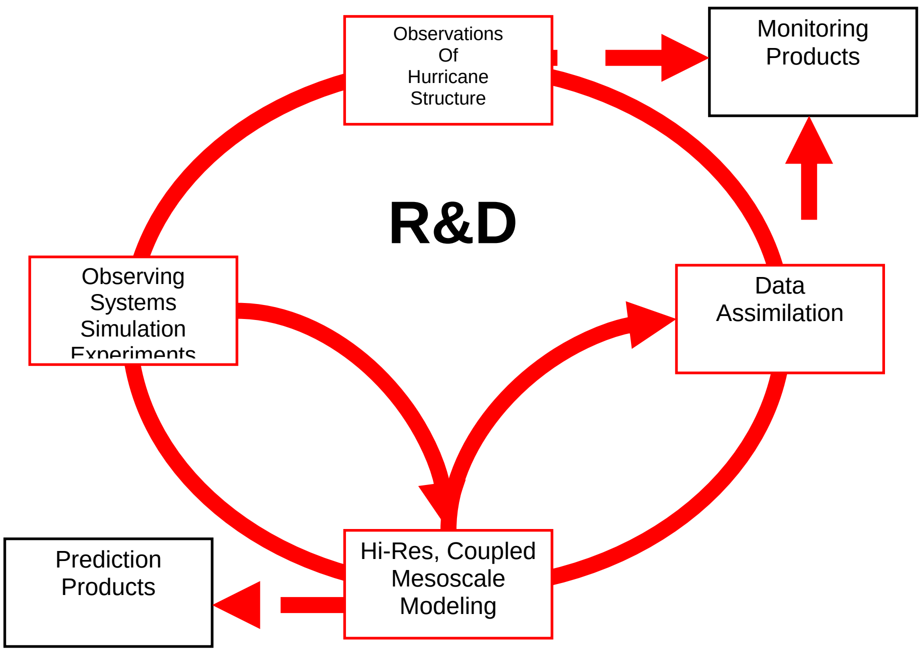


Figure 2. The central role of research and development in addressing hurricane forecast improvements.

A series of focused research workshops were held under the USWRP around a decade ago, with the goal of identifying key research issues and directions. These resulted in a series of reports, among them being the PDT-5 report (Marks and Shay 1998), which recommended the following:

The key research issues brought before the HIRWG have substantial overlap with PDT-5 on current NHC priority needs, including:

- Time of onset and magnitude of rapid intensification;
- Decay and re-intensification cycles; and
- Time of onset and magnitude of rapid decay.

Several advances resulted from the previous USWRP effort, including support for the Joint Hurricane Test Bed and the development of the Hurricane WRF (HWRF). However, the vast bulk of the work envisaged by the scientists involved in the planning process was never adequately funded and this may factor into the continued lack of progress with hurricane-intensity forecasting. The HIRWG has concluded that there are several interrelated reasons for this lack of progress:

- The improvement of intensity forecasting is a high priority for many, but no "national need" has been articulated by national leadership;
- Whilst there is a broad range of activities – observational, R&D, tech transfer, operational – being conducted inside and outside NOAA, there is again no national leadership;
- The interconnections, coordination and collaboration among related activities range from poor to good and there is a tendency towards fragmentation rather than coordination;
- Commitment commensurate with the complexity of problem is lacking, with limited human resources and financial support, and no national focus.

There are, however, numerous bright spots on which to build, and these are addressed in the following sections.

Recommendation: Sufficient resources and national leadership should be dedicated to enable the high-priority research-and-development activities described recommended below to be 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.

4 Observations

The North Atlantic is the locale of the best hurricane-observing capacity in the world, with a combination of satellite, aircraft, oceanic, radar and balloon observing systems. New sensors that are scheduled for deployment in the next few years will further enhance this capacity. However, the observing system is constantly under budgetary threat, and this threat is particularly apparent in the potential delays, or even cancellations, of planned observing upgrades. There are also a few conspicuous gaps of relevance to intensity and structure determination, such as the near-surface-layer wind and thermal structure and specification of the ocean-surface fluxes.

It is not our intent here to present a comprehensive survey or assessment of the current observing system. Rather, we concentrate on gaps and concerns, both with the actual observations and the manner in which they are incorporated into the forecast process.

4.1 Observing System Simulation Experiments (OSSEs)

Observing hurricanes and tropical storms utilizes a combination of static (radiosondes, ground radars, many satellites) and mobile (aircraft and some satellites) observing systems. Considerable experience and expertise have been developed in the optimal ways of deploying the mobile systems, and NOAA should ensure that this expertise is retained and further developed. But the system is not unchanging; it evolves to encompass new instruments and in response to new knowledge and forecast systems.

OSSEs are a powerful and relatively inexpensive way: of assessing the impact of potential new observations; for determining the impact of removal of current observing systems; and for refining and redirecting current observing practices. Any new or proposed observing system or major instrument should carry out an OSSE as part of the preparation for its deployment, and also as a way of redefining the overall observing strategy to include the particular instrument or system. Further, with the advent of new forecast techniques, including high resolution models, OSSEs would provide an excellent way of retuning the observing system to the forecast needs.

Recommendation: 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 system.

4.2 Satellite Observations

Current satellite systems combine dense spatial information with periodic revisit, but a relatively poor vertical resolution. These data are critical for monitoring tropical storms over the ocean, and provide both detailed observations and the larger-scale context for targeted aircraft and related observing systems. Moreover, these data are important to improve reanalysis data and initial conditions for hurricane forecasting through data assimilation. There are two different types of satellites: (near) polar-orbiting and geostationary. Polar-orbiting satellites observe the hurricane for brief intervals only twice a day and they may miss important information. Therefore, the synthesis of different satellite data (e.g., QuiksCAT, SSM/I, and ERS-2) is important. Geostationary satellites provide continuous coverage (every few minutes in some cases), but their high altitude (much higher than polar orbiters) impedes attaining desired resolution.

A summary of current satellites of importance to hurricane forecasting is provided in Table 1, which is based on an informal report provided upon a request to the USWRP in 2002 by C. Velden (CIMSS) and M. DeMaria (NOAA/NESDIS). Several satellites observe winds over the ocean, which are important to hurricane intensity and forecasts, such as QuikSCAT, Special Sensor Microwave Imager (SSM/I), and European Space Agency ERS-2. The primary advantage of microwave observations is that they can provide information below the cloud top. However, most of those data are contaminated by heavy rainfall and the signal is saturated at high winds. In addition, due to the insufficient spatial resolution, the observations can potentially miss high wind data.

Satellite Instrument	**Type**	**Observations**	**Resolution**		**Deficiencies**
			Horiz.	**Vert.**	
Quickscat	PO	Sea surface wind vectors Ocean waves	25 km	n/a	Saturates at high winds Low resolution Attenuation in heavy rain areas
SSM/I	PO	Sea surface wind speeds Total precipitable water Rain rate	25 km	n/a	Saturates at high winds Low resolution Attenuation in heavy rain areas
ERS-2	PO	Sea surface wind vectors Dynamic height	50 km	n/a	Saturates at high winds low resolution
AMSU	PO	Sounding temperature	50 km	??	Low resolution
AMSR	PO	Sea surface wind speeds Total precipitable water Rain rate	21 km ?? 5.4 km	n/a	
AVHRR	PO	SST	4 km	n/a	
GOES	GS	Hurricane position and intensity, cloud tracking winds	n/a	n/a	Height estimation

Table 1: Summary of current satellite systems relevant to hurricanes

Several new satellite systems are scheduled for operation within the next 5 years. Some of these will expand on current observing capacity, and some will bring hitherto unavailable observations to the mix. These are summarized in Table 2.

Satellite Instrument	Type	Observations	Resolution		Deficiencies
			Horiz.	Vert.	
Cosmic	PO	Thermal soundings and total precipitable water	300 km	100 m	Nil
ASCAT	PO	Sea surface wind vectors			
ATMS	PO	Sounding temperature Precipitation	33 km	??	
GOES-R	GS	Higher spatial and temporal resolution than GOES data			

Table 2: Summary of planned satellite systems relevant to hurricanes

Satellite systems are designed to provide a much broader range of observations than just for hurricanes, and in some cases the hurricane data are a bonus. Thus, the hurricane community is generally more of a benefactor of larger priorities than a direct driver of satellite systems. However, there are some instruments that are of considerable benefit to hurricane observations (for both research and operations). One example is the TRMM radar. Whilst this can observe hurricanes for only brief periods twice a day, these observations have been lauded by forecasting offices around the world. TRMM is an experimental NASA satellite, and was saved from decommissioning last year only by a concerted campaign. Unfortunately, it is very much beyond its scheduled lifetime and a replacement is many years away. Another is NPOESS, which is scheduled for launch in the near future, but is pending recertification.

The use of satellite data to estimate tropical cyclone intensity (e.g., the objective Dvorak technique) and structure has shown promising results (Brueske and Velden, 2003; Demuth et. al. 2004; Velden et al. 2006). Efforts should continue on further development and improvement of such techniques. We note, and discuss further in Section 5.3 that the assimilation of satellite observations to improve hurricane forecasts has not been fully explored and more efforts on this direction should be encouraged.

Recommendation: The strengths and weaknesses of current and past satellite observations for hurricane forecasting should be fully evaluated using OSSEs and with direct involvement from that portion of the academic community focused on operational products, with the aim of developing a comprehensive plan in support of current initiatives and to recommend future directions.

4.3 Manned Aircraft

Manned aircraft have provided critical atmospheric and oceanic observations of the hurricane core and near environment for over 40 years. They have demonstrably contributed substantially to improvements in forecasting, both from the direct observations and from the research and understanding that they have enabled (****). Because of the cost and the need to replace aging aircraft, the reconnaissance program comes under threat of closure from time to time. The HIRWG saw no evidence of a current threat, but there is a need to constantly monitor this situation. The current research and operations aircraft that have demonstrated capability for hurricane missions are listed in Table 3.

Aircraft	Speed/Endurance/ Range	Altitude	Instruments	Mission
NOAA G-IV	450 kt, 9 h, 4000 nm	45,000 ft	1-Hz flight-level data (inertial and GPS navigation), GPS dropwindsonde, Workstation with HAPS data processing, SATCOM (64 kBd) supporting data transfer, voice, and Xchat (developing Doppler radar capability available 2008)	Operations and research, primarily environmental monitoring (with Doppler radar addition NOAA is developing capability to operate the G-IV in the storm core)
NOAA WP-3D (2)	250 kt, 10-h, 2500 nm	500-20,000 ft	1-Hz flight-level data (inertial and GPS navigation), GPS dropwindsonde, ocean expendables (AXBT/CP/CTD), SFMR, cloud microphysics, electric field, LF conventional radar and TA Doppler radar, Workstation with HAPS data processing, SATCOM (9.6 and 64 kBd) supporting data transfer, voice, and Xchat. Other instruments added in TC missions include the NASA scanning radar altimeter (SRA) to map 2-D wave spectra, NESDIS/ UMASS scatterometer/ profiler (IWRAP), NOAA/ARL and UM turbulence probes for wind and thermodynamic variables	Operations and research, primarily inner core reconnaissance and research into different physical processes (vortex structure and interaction with ocean, environment, rainbands, microphysics and precipitation physics, upper ocean and waves
USAF WC-130J (10)	250 kt, 12 h, 3000 nm	500-30,000 ft	1-Hz flight-level data (inertial and GPS navigation), GPS dropwindsonde, ocean expendables (drifting buoys and floats), SATCOM (encrypted DoD) and in the next two years SFMR will be added	Operations, primarily reconnaissance, but also environmental monitoring
NASA ER-2	400 kt, 9 h, 3600 nm	60,000 ft	instrument payload driven by proposals – some available in CAMEX and TCSP missions	Research

Aircraft	Speed/Endurance/ Range	Altitude	Instruments	Mission
			include: 1-Hz flight-level data (inertial and GPS navigation), GPS dropwindsonde, SATCOM, EDOP vertically profiling Doppler radar, numerous passive remote sensors	
NASA/University of North Dakota DC-8	360 kt, 10 h, 3600 nm	27,000 to 39,000 ft	instrument payload driven by proposals – some available in CAMEX missions include: 1-Hz flight-level data (inertial and GPS navigation), GPS dropwindsonde, SATCOM and numerous active and passive remote sensors	Research
NRL P-3	250 kt, 10-h, 2500 nm	500-20,000 ft	1-Hz flight-level data (inertial and GPS navigation), GPS dropwindsonde, SATCOM (9.6 kBd), NCAR ELDORA Doppler radar	Research
Aerosonde	50 kt, 24 h, 1200 nm	200-20,000 ft	1-min flight level data (GPS navigation), SATCOM	Research

Table 3: Current manned aircraft with demonstrated capability for research and operations reconnaissance of tropical cyclones.

The HIRWG endorses the installation of radar on the G-IV, which will provide a substantially expanded capacity for it to provide detailed information on tropical cyclone core and rain-band structure. However we emphasize that the full benefit will not be achieved unless it is accompanied by implementation of a data-assimilation system capable of ingesting these data into forecast models. This will be referred to further under Section 5.3. We also view with concern information that the deployment of the SFMR on USAF c130s may be delayed. This instrument has proven to provide valuable surface observations of the strong wind region, and its speedy implementation is encouraged.

Recommendation: The planned G-IV radar implementation is endorsed, as is the SFMR deployment on USAF C130s

4.4 Unmanned Aerial Systems (UAS)

UAS have rapidly developed a niche for undertaking long-endurance observations under difficult and dangerous conditions that preclude manned operations or place them at high risk. Two basic types of aircraft have been brought before the HIRWG: High-Altitude, Long-Endurance (HALE) and Low-Altitude, Long-Endurance (LALE). Specific aircraft that have been proposed by NOAA staff for consideration are listed in Table 4.

Aircraft	Speed/Endurance/Range	Altitude	Instruments	Mission
Global Hawk	340 kt, >30 h, 12,000 nm	65,000 ft	Camera, no operational met sensors (but via/IR/MW/SAR	Research and Operations, Environmental

			packages, flown extensively) Dropsonde and radar proposed	monitoring
Aerosonde MKIV	80 kt, >30 h, 2000 nm	20,000 ft	Flight level PTU and Winds, SST, cloud physics, camera; surface winds and sea state under development	Research and Operations, low-level reconnaissance

Table 4: Specifications for the Global Hawk and Aerosonde UAS.

However, we note that there is a wide range of UAS flying and in various stages of development. Their endurance and altitude extend out to months and from the surface to 100,000 ft. Each has advantages and disadvantages, all are still at the experimental stage and many are comparably as, or more expensive than equivalently performing manned aircraft. They hold considerable promise for long-period loitering and for obtaining observations in, for example, the region close to the surface where damaging winds and important energy exchanges occur. The HIRWG was not able to undertake sufficient investigation to examine comprehensively the relative benefits of UAS vs. manned aircraft and other observing systems. We recommend that this be undertaken by a special commission and that it include the use of OSSEs to fully determine the potential impact.

Recommendation: NOAA should establish an independent committee to examine the potential role of UAS for tropical-cyclone observations. This examination should include use of OSSEs to assist objective determination of the potential impact of these observations.

The HIRWG notes that a successful trial reconnaissance into Ophelia was made using the Aerosonde UAS in a joint NOAA/NASA program. The Director of the NHC has indicated a strong interest (cite reference) in further trials to ascertain if this aircraft can provide near-surface observations that are critical to intensity forecasting, and are currently poorly sampled by other observing systems. The HIRWG endorses this interest as a logical step in developing experience with the operation of such systems.

Recommendation: 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.

4.5 Surface Observing Systems

Surface observations are obtained from two primary sources:

- Land and oceanic systems, deployed as part of the overall observing system, which come under tropical-cyclone circulation; and

- Targeted instruments deployed by aircraft over the ocean and by surface transport along the coast, to provide specific observations for tropical-cyclone research and operations.

The most important functions of surface instrumentation is to provide:
- Calibration for remote sensing instruments;
- Ocean surface conditions and oceanic heat content;
- Surface wind structure, especially at landfall, an event for which considerable controversy often arises concerning the strength of winds.

The HIRWG was presented with no evidence of there being major deficiencies in the current deployments. However, we recommend that this current level of deployment be maintained. A need was identified for improved survivability of wind instruments during hurricane landfall, particularly for very intense winds. Two novel approaches were also presented:
- Use of a UAS to drop long-loitering microprobes directly into the eye;
- Use of the oil platforms in the Gulf of Mexico for installing surface observing equipment, for both research and operations, including locating ground sites for GPS soundings.

4.6 Land-Based Radar

Land-based radar are a critical observing tool for the precipitation structure of landfalling tropical cyclone. Whilst their range over the ocean is limited, they provide valuable information on the eye size and position and the presence of outer bands that bring periods of rain and high winds well before the cyclone core crosses the coast. Examples of local wind and weather systems that have been identified only by radar include, boundary layer rolls (and their associated local wind streaks) regions of intense convective rainfall, and broad analysis of the overall rain structure.

The USA is well served by the extensive set of NEXRAD radars, and by mobile Doppler radars that are deployed in the path of approaching hurricanes. These are networked in a manner that well serves the direct forecast needs, but the data are not included in current numerical model forecasts, an inadequacy that is further addressed in Section 5.3.

Lightening detection systems also provide valuable information on regions of severe convection and where lightening may adversely effect vulnerable systems, such as power grids.

The HIRWG was presented with no major issues associated with the current network, though we note the need for robust communications and emergency power systems that are able to withstand high wind conditions and the desirability of improved networking of all radars in the Gulf of Mexico and Caribbean.

4.7 Balloons and Rawinsondes

The reliable rawinsonde remains a staple observing tool, especially for observing the upstream environment for tropical cyclones approaching the US. Whilst this capability should be sustained, there are no specific recommendations for changes to this system. The HIRWG also received suggestions for novel approaches, including automated launching systems on islands and the use of mylar constant-pressure balloons in swarms to provide observations within the hurricane circulation. We recommend that these approaches be considered as part of the longer-term assessment of the observing array, together with OSSEs to ascertain their potential impact on forecast errors.

5 Numerical Modeling of Hurricane Intensity and Structure

Discussion within the HIRWG on the best approach to improving numerical forecasts of the intensity and structure of hurricanes has evolved around three main themes:

- The desirability of locally high-resolution predictions to enable the timely, explicit prediction of salient details of the hurricane core, a recommendation of previous national review panels (e.g., Marks and Shay, 1998);
- The recognition of the limits of current NOAA computing capacity and the existing NOAA schedule for upgrade, and the consideration of potential alternatives of using simpler and much less computer-intensive methods;
- The tradeoff between using available computer power for deterministic forecasts at high resolution or ensemble forecasts at lower resolution, and use of simpler models.

The reader is cautioned that, throughout this chapter "*resolution*" refers to the horizontal and vertical grid spacing of the model. The actual phenomena that are resolved are typically several grid lengths in scale.

Whilst the HIRWG advocates and supports a balanced suite of techniques, including advanced models, statistical techniques, and more simplified modeling approaches, we are of the view that major improvements in hurricane intensity and structure forecasting require adoption of high-resolution numerical modeling of the hurricane core. Depending on the way in which this objective is achieved, this might require enhanced, even greatly enhanced, computing and human resources. In particular, the current standard hurricane computing cycle at NCEP may be sufficient to support good quality-track forecasting, but it is not adequate to support forecasting of the rapid evolution of eyewall structure, and consequent change in hurricane intensity, via high-resolution modeling. Moreover, the staff and resources required to maintain and upgrade the operational computer models is too small given the complexity of the tasks.

In this section we:

- Address the current NCEP hurricane modeling activities and directions;
- Describe current hurricane research modeling efforts of relevance;
- Elaborate on the need for advanced, high-core-resolution modeling and the potential benefits that are anticipated to result;
- Discuss the need for, and approaches to, advanced data assimilation in support of the modeling effort;
- Discuss the potential support provided by simpler models; and
- Consider approaches to model verification.

Whilst the HIRWG has explored many aspects of the requirements for hurricane modeling, this assessment was necessarily limited by the time available. The following discussion will indicate the complexity of the problem and the need for a multi-agency approach to its solution. This discussion will lead to a recommendation for a standing SAB oversight board to guide the effort.

5.1 Hurricane Models

5.1.1 Operational Hurricane Operational Models at NCEP

GFS (Global Forecast System): Supported by the Global Data Assimilation System (GDAS), NCEP's Global Forecast System Atmospheric Model is run at a horizontal resolution of Spectral triangular 254 (T254); Gaussian grid of 768X384, roughly equivalent to 0.5 X 0.5 degree latitude/longitude with 64 unequally spaced levels in the vertical. This model provides real-time operational forecasts four times a day out to 16 days into the future. It is one of the skillful hurricane track models used by the NHC, but it has no skill at hurricane-intensity forecasting and is not used directly by the NHC. Its major role in hurricane intensity forecasting is to provide boundary conditions for the specialized hurricane models.

GFDL Hurricane Model: Since 1995, the GFDL Hurricane Prediction System has been utilized to provide operational guidance for forecasters at the NHC in both the North Atlantic and East Pacific basins. In addition, a version of the GFDL model (GFDN) has been used by the Navy to provide operational guidance for storms in other ocean basins. The model is a primitive-equation model formulated in latitude, longitude, and sigma coordinates, with 18 vertical sigma levels. The nested grid system provides for a highest resolution of 9 km. The forecast model has been coupled with a high-resolution version of the Princeton Ocean Model (POM). The GFDL track forecasts have improved substantially since 1995 and show real skill, but for intensity there has been little, if any, real improvement.

Hurricane Weather Research and Forecast Model (HWRF): The HWRF is being developed at NCEP and is proposed for operational hurricane forecasts starting in the year 2007. The initiation of HWRF model began with a uniform-mesh prototype system which was installed and tested at NCEP during the 2004 and 2005 seasons. This system includes the NMM dynamic core and a multiple nesting capability. The operational configuration has not been finalized, but is expected to be around 9 km in the horizontal and will include 3DVar initialization and coupled ocean and wave models. As this will be the next-generation hurricane model, further work on the GFDL model has ceased, but it will be kept in operations for the time being. The HIRWG supports this initiative but recognizes that the design of the initiative was limited by the available budget and access to computing power. In particular, there are inadequate staff allocated to this important function and the interactions with, and use of, the external community in this development have been poor.

Recommendation: The planned HWRF Version 1 implementation should be implemented in a timely manner and with the best possible features; we consider that this implementation will necessitate an enhanced effort and funding in 2006 and in subsequent years for development of the next-generation HWRF in conjunction with the external research community.

5.1.2 Hurricane Research Models

NCAR Advanced Research WRF Model (ARW): The US Weather Research Program (USWRP) invested in the Weather and Research Forecast (WRF) model development as a means to more effectively and efficiently transition the advances in research modeling to operations. The ARW developed by a combination of community and NCAR scientists provides a compatible modeling infrastructure for a wide range of academic, government laboratories and operational (including a number of international) centers. Patterned after the community MM5 system, the facility support includes a help desk, regular tutorials, and workshops that allow many (more than 3500 registered users) modelers to test new modeling ideas and developments, which thus fulfills the USWRP goal. The ARW model has very high level conserving properties, multiple physics options and is built into a software architecture allowing for computational parallelism and system extensibility. It has been used in a broad spectrum of applications ranging down to resolutions of less than 100 m. It has 3DVAR and Ensemble Kalman Filter data assimilation systems and a 4DVAR will be operational with the USAF in 2008.

The HIRWG has been presented evidence that new research models from several institutions should have an important role in future improvements for hurricane intensity forecasting. This varies from trying out new ideas to development of new physics and other modules, and improvements in understanding. In particular, the extensive research being done with the ARW provides a remarkably broad research resource in support of future operational implementations. The HIRWG view is that this resource has the potential to lead to a version 2 of HWRF that is substantially improved, but that this will require a broader, collaborative approach than is currently in place. This need for a collaborative effort is the basis of several recommendations, including:

Recommendation: 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 with operations giving serious consideration to research developments and research noting operational needs in setting their research priorities.

Recommendation: The Developmental Test Center and Joint Hurricane Testbed should be tasked to improved links with NOAA operational efforts with the wider research community; this should include an evaluation and intercomparison of NOAA

models with community models and the establishment of enhanced visitor and post-doctoral programs.

5.2 Advanced, High-resolution Numerical Modeling of Hurricane Intensity and Structure

Successful simulation of the basic processes of hurricane structure and intensity changes requires resolution and model physics that are capable of resolving the following:

- Inner core dynamics such as mesoscale organization of convective clouds, asymmetries and eye-wall replacements;
- Upper tropospheric circulations and their interactions with the tropical cyclone;
- Interaction with the upper ocean including surface energy exchanges and forced upwelling and cooling.

Prediction of collateral effects such as accumulated precipitation, storm surge, ocean waves, interaction with topography, and tornadoes also depend on accurate structure and intensity predictions.

As shown in Fig. 5.1, the GFDL results over the past five years for forecasting tropical cyclone intensity have barely improved and are not better than the statistical-dynamical techniques that continue to be improved with Joint Hurricane Testbed funding. This is in direct contrast to the remarkable success that has been achieved with hurricane track forecasting by the GFDL and similar models. The committee is of the firm opinion that a major reason for this lack of progress in intensity forecasting has been the lack of sufficient resolution in the GFDL model.

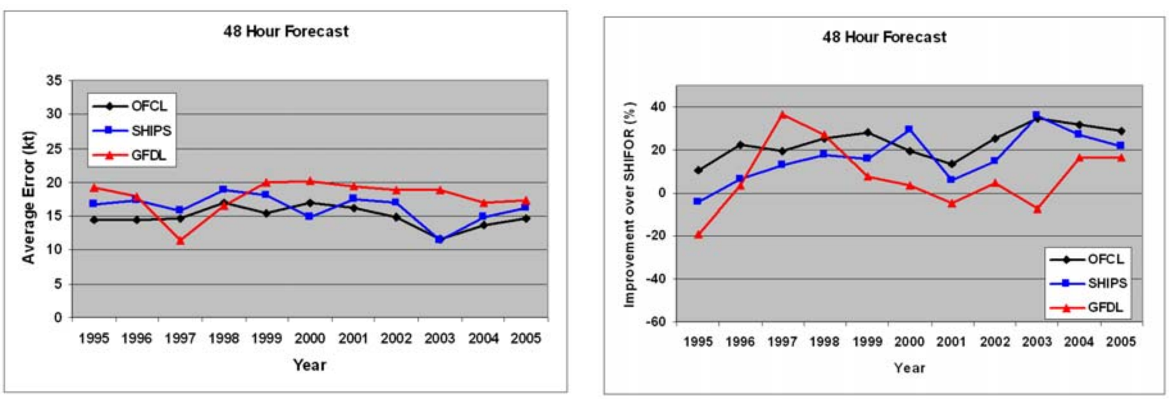


Figure 5.1. GFDL intensity forecast trend since 1995 for the critical 48 h forecast period, compared to the SHIPS statistical technique and the NHC forecasts (OFCL). The left panel is the actual errors and the right panel shows the skill relative to the SHIFOR statistical technique. Provided by Mark Demaria (pc 2006).

There are several reasons why very high resolution (small grid spacing) is required to improve the accuracy of model forecasts of hurricane intensity. Foremost is the requirement that the relevant details of the eye region are captured. Since a typical hurricane eye is approximately 40-60 km across, this requires a grid spacing of at least 5-

10 km. Moreover, substantial research extending over several decades has emphasized the importance of details of the eye-wall region in the overall intensification process. The committee has been presented with evidence of the importance of higher resolution in capturing both the initiation and the life cycle of an eye-wall replacement cycle, which correlates strongly with changes in hurricane intensity. Such features require grid spacing of 1-2 km to be adequately simulated.

A second requirement for very high resolution is to simulate the details of the moist convective processes that are critical to intensification. Resolutions of coarser than 5 km grid spacing require the use of some form of convective parameterization, which cannot take into account important mesoscale organization and structural details. Moving to resolutions finer than 5 km enables explicit modeling of the convective systems (using only cloud-physics parameterizations).

Over the past several years, NCAR has been running their ARW model in real-time simulations of landfalling hurricanes as part of their overall development effort. These forecasts have not utilized an interactive ocean, and they have been initialized with either the GFDL initial condition, which uses a bogus vortex, or the coarse grid GFS, both of which only poorly capture the salient details of the core structure. The forecast verifications for the 2005 season (Fig. 5.2) indicates that both the 4 km forecast have similar skill as other techniques for the first 36-48 hours and then both provide substantial improvement over other techniques to the ending time of their runs. Figure 5.2 leads to two important inferences:

- The poor initial condition provided by the GFDL bogus inhibits forecast accuracy for the first 36 hours or so;
- At longer time periods, the combination of more accurate information flowing into the nested domain through the boundary conditions, relatively high resolution, and explicit computation of cumulus convection provides a very substantial forecast improvement.

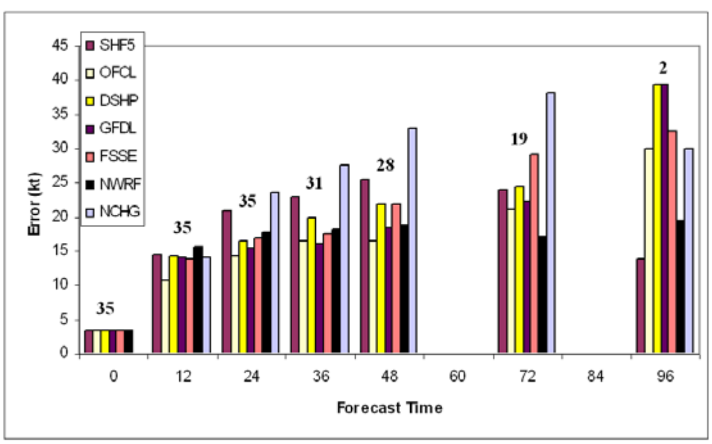
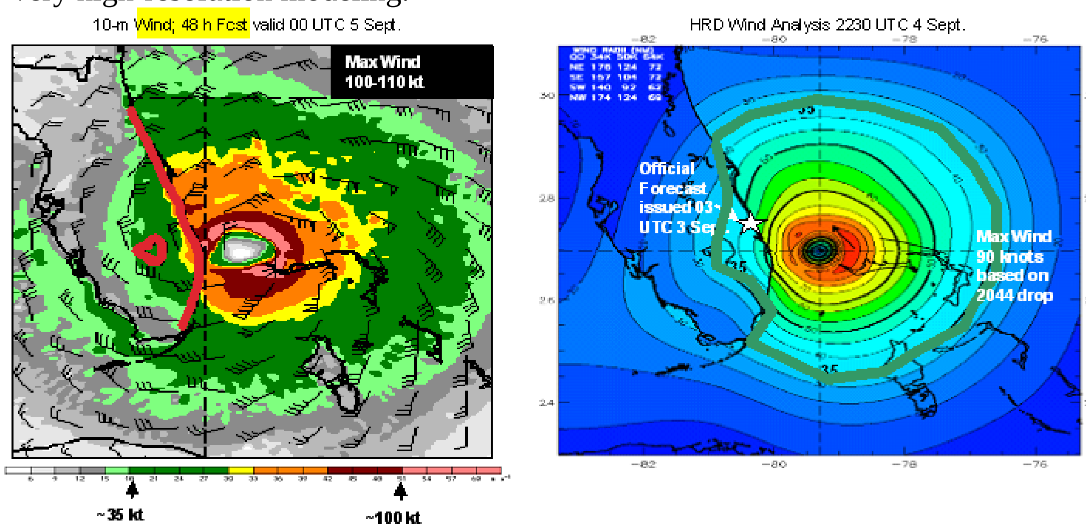


Figure 5.2: Homogeneous comparison of the 4 km NCAR WRF with a number of other forecast techniques for real-time predictions conducted in the 2005 hurricane season. The numbers above each time group indicate the number of forecasts. SHF5 and DSHP are statistical techniques, OFCL is the NHC forecast, GFDL is the GFDL model, FSSE is the Florida super ensemble, NWRF is the NCAR WRF, and NCHG is no change in intensity

A somewhat surprising result was the lack of a major improvement in going from 12 to 4 km resolution (not shown). This resolution requirement aspect has been further investigated by Shuyi Chen (U. of Miami). In a presentation to the committee, she showed a remarkable improvement in skill for both the MM5 and WRF model prediction of intensity when the grid resolution ~~is~~ was increased to below 2 km (Fig. 5.3). NCAR has also conducted further simulations that confirm this result. While further research and a broader range of experiments are required, these preliminary results indicate the potential for a major improvement in intensity forecasts by going to very high resolution.

The impact of a hurricane involves more than just the prediction of the maximum wind. Also of importance are the impacts on society caused by the overall hurricane structure, including the wind-driven storm surge, extent of wind damage, and rainfall. Recent research also has shown a great potential for use of high-resolution models to more accurately portray the relevant structural features several days in advance of landfall (e.g. Fig. 5.4). Again these results are indicative rather than prescriptive, but they point toward~~s~~ priorities for further research. This forecast capacity points to the importance of both vortex dynamics and environmental interactions, both of which can only be obtained by very high-resolution modeling.



ARW 48-h Forecast 10 m wind

NOAA/HRD 10-m HWind Analysis

Figure 5.4. Indication of the potential for prediction of wind structure details using the 4 km NCAR WRF: left panel the 48-h forecasts of surface winds, right the HRD Wind Analysis for the same time. The green line on the right panel corresponds to the edge of the 35 kt winds (green area) on the left panel.

In addition to testing very high-resolution models future investigations should include improvements to cloud physical parameterizations, together with the coupling of the atmosphere with the ocean, and the effects of ocean waves on this coupling. Each of these physical processes has a potential for improving both intensity and the overall wind and precipitation structure of hurricanes.

Recommendation: NOAA should evaluate the feasibility of providing the computing and system capability to produce 1-km-resolution hurricane forecasts, an objective especially relevant for storms that are deemed likely to affect the US within 5 days.

Recommendation: Support should be provided for high-resolution modeling experiments, research and development using recent field experiments such as CBLAST and RAINEX.

Recommendation: Additional field experiments aimed at both validating high-resolution coupled models and assessing observing-system configurations developed from OSSEs should be encouraged.

5.3 Data Assimilation for Hurricane Modeling

Because of the need for nested grids to achieve sufficient resolution for intensity forecasting, numerical simulation of tropical cyclones is a combination of an initial and boundary value problem. Therefore, providing accurate initial conditions for numerical model forecasts is one of critical components to better predict hurricane intensity and track. While the bogus vortex developed for the GFDL has been successful in helping improve track forecasts, evidence submitted to the HIRWG indicates that such a poor representation of the initial structure is a major limitation to improved intensity forecasting, which thus must be a focus for research and development. A further area of uncertainty arises from factors such as the use of raw measurements vs. retrieved products, observation errors, background errors, data quality control, etc.

Since tropical storms generally lie over the open ocean, where conventional data are sparse, a combination of remote sensing from satellites and aircraft reconnaissance provide the critical observations for the model initial conditions, which must be handled in a logical manner using data assimilation techniques. Current forecast systems (GFDL) do not adequately assimilate such data. While the HWRF version 1 will improve this there is still a major disconnect between the available data and the assimilation of these data into the hurricane forecast models. For example, the excellent aircraft and satellite and radar data collection (both Doppler winds and reflectivity) are not included at all and nor are the available land-based radar data.

The HIRWG is of the view that the full advantages of moving to high resolution modeling will be retarded unless there is a concomitant move to develop suitable data assimilation techniques. Research into optimal ways of including high-resolution, ad-hoc data (such as available from remote sensing and aircraft reconnaissance) is strongly supported.

Recommendation: Airborne and surface-based radars offer the best opportunity to observe mesoscale fields in 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.

Data assimilation techniques may be broken down into time dependent and static modes:

- Static modes include 3-Dimensional Variational data assimilation (3DVAR), which may include a cycling component, and optimal interpolation;
- Time-dependent modes include 4-Dimensional Variational data assimilation (4DVAR), nudging, and Ensemble Kalman Filtering (EnKF).

Data assimilation is still an open research field and there is no definitive evidence of which approach is best for tropical cyclone intensity forecasting. The HIRWG notes, and fully supports, moves by NCEP to include a 3DVar assimilation in the HWRF due for operational release in 2007. However, the use of time-dependent approaches, such as 4DVAR, at major international centers has provided substantially improved forecasts of general meteorological systems and there is every expectation that similar results would be obtained with tropical cyclones.

Recommendation: 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.

Recommendation: 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.

5.4 Potential Contributions from Simple Models and Statistical Techniques

While the HIRWG has strongly recommended a major emphasis on numerical modeling, and particularly high-resolution modeling, in improving intensity forecasting, we also see the need for continued development of small models and statistical approaches. The history of improvements in track forecasting is of relevance here. Initially statistical and simple models provided the best forecasts, but as numerical models developed these were surpassed and the last statistical track forecast technique at NHC was retired in 2006.

Small models and statistical techniques are defined here as possessing four crucial characteristics:

- Small models are based on approximate equations derived from the laws of physics;
- Statistical models use relationships that are empirically derived from associations with easily observed parameters;
- Access to supercomputers is not required to run them; and,
- The input data requirements are modest.

This also means that forecasts from such models can be made available earlier than those from more complex numerical models. They also have the advantage that development time is generally short and they can be brought to operations, or modified much quicker than can numerical models. The disadvantage lies in the limited subset of information that can be obtained compared to a comprehensive numerical model. Examples of a dynamical model and a statistical technique include:

- The Coupled Hurricane Intensity Prediction System (CHIPS) model (Emanuel ***) which is basically an axisymmetric model plus an empirically parameterized vertical wind shear effect and a 1D ocean model; and,
- The statistical SHIPS and DSHIPS models (DeMaria et al. 2005), which utilize associations between environmental variables and intensity, and include some theoretical reasoning.

The HIRWG has received inputs suggesting that simple models more focused on the physics of rapid intensification, and boundary layer physics understanding gained laboratory and engineering studies, may be viable on shorter time scales.

Recommendation: Researchers (inside or outside of NOAA) are encouraged to develop and then test statistical and other forecast techniques in operational data streams and, if successful, seek Joint Hurricane Testbed funding to transition the model to NHC.

5.5 Derived Products: Modeling Needs

An important, but somewhat neglected outcome of advances in hurricane modeling capacity, is the potential for specialized derived products to be provided in support of specific community needs. These include: storm surge, ocean waves, GIS-based direct impact assessments, and special industry requirements (such as the insurance and offshore oil industries).

The critical need for storm surge forecasts is an accurate track and good representation of the surface wind field near landfall. Because of the very high sensitivity to relatively small track errors, surge forecasting is normally accomplished by probabilistic approaches, or worst case scenarios (such as the Maximum Envelope of Waters technique, Jelesnianski ****). These are normally derived from relatively simple wind fields that are often analytically defined. However, the increasing sophistication and detail of numerical models enables a rethink of this process. Relevant research directions could include innovative ways of deriving probabilistic surge forecasts from model ensembles and use of model output in post-analysis mode to support ecological, design and damage assessments.

Wave forecasting is less dependent on the actual track, but is highly dependent on the detailed structure of the wind field across the entire hurricane. Again this is an area where detailed models will be of considerable benefit. The HIRWG notes, further, evidence that coupling an ocean surface wave model in a two-way sense to the operational atmospheric model may provide improved forecasts of the surface wind field.

An exciting new development has been the coupling of a numerical forecast of surface winds and rainfall to impact models, which use a GIS-based view of vulnerable infrastructure together with damage assessment modules to directly forecast the hurricane impacts. This provides the potential for direct advice to emergency managers of likely disruptions to infrastructure, optimal evacuation routes, and likely recovery times for critical systems (such as power lines and generator stations). A collaborative program between NCAR and Los Alamos National Laboratory has lead to real-time testing of a prototype system in 2005, which will be continued in 2006. NOAA should follow this program closely and consider how it could be incorporated into a next-generation warning system.

Recommendation: 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.

5.6 Related Computing Issues

To be written

5.7 Hurricane Model Validation and Verification

The increasing capacity of numerical models to forecast not only the maximum wind, but details of the wind and precipitation structure of the hurricane, combined with the expected moves towards moiré direct impacts forecasting, requires a reconsideration of the way in which validation and verification is accomplished. The current focus on maximum wind and track for verification has provided a good, logical way of tracking improvements to the system. But the HIWRG is of the view that this will not be suitable for the increasingly complex societal requirements of the forecast system. We therefore recommend that a careful study be made of new approaches to verification, and those that provide a wider assessment of the usefulness of model forecasts to addressing the hurricane intensity and structure requirements.

Recommendation: The current verification based on track and maximum intensity should be retained for continuity. But new and more comprehensive verifications that can fully indicate the quality of the intensity and structure forcecast should be developed

Diagnostic evaluation tailored to hurricane intensity is an area in which the work of EMC/NHC may be complemented by contribution from universities and other laboratories. Besides the conventional parameters such as the role of SST anomalies, wind shear, lower-tropospheric vorticity, etc., examination of the impact on the accuracy of NOAA real-time operational hurricane-intensity forecasts should be made with respect to: the mode of organization of convection, angular-momentum histories, role of vortex Rossby waves, scale interactions among cloud and hurricane scales, potential vorticity and diabatic potential-vorticity contributions, effect of dry-air and Saharan-air-layer intrusions, microphysical sensitivity, data sensitivity, adaptive observational strategies, issues of resolution, physical parameterizations, grid nesting, coupling ocean and atmosphere, and even the formulation of dynamical core. The support of the wider research community is needed to assess which of these issues significantly impact hurricane intensity, especially major-hurricane intensity. Those phenomena that do not have demonstrable, significant impact on hurricane intensity probably lie outside the scope of priority issues for a mission-directed, goal-oriented agency such as NOAA, which is tasked to provide timely accurate forecasts, notwithstanding Congressional allotment of perennially austere funding.

6 Structuring a *Research* and *Applied Development* Program

6.1 Purpose

A hurricane is a spectacular example of a self-organizing mesoscale convective system on a vast horizontal scale. Aircraft reconnaissance over the past four decades has provided fundamental insights into their kinematic and thermodynamic structure. In broad terms, a hurricane is a natural Carnot engine (Emanuel 1986): it extracts heat from the underlying ocean at approximately constant temperature and this heat is transported adiabatically to the upper troposphere and finally is cooled by infrared radiation to space. The result of this thermodynamic cycle is the creation of a swirling vortex that dissipates the bulk of its kinetic energy in the atmospheric boundary layer. Many scientific questions about the thermomechanics of these Carnot machines remain unanswered, and we believe that some of these research questions must be confronted in order to break the current hurricane intensity forecast impasse.

A successful research and development program aimed at improving hurricane intensity forecasts must be multifaceted, provide opportunity for scientific innovation and discovery and at the same time be focused on the key motion scales believed to be important to the intensity problem. Here we first discuss some key research activities and needs, together with an overview of some of the related processes. Areas with high potential for an operational return are then discussed, with recommendations for foucssed research support.

6.2 **Background on Internal Hurricane Processes**

In addition to known, but still not fully understood, environmental (synoptic) influences on hurricane intensity, such as vertical shear, the Saharan air layer (Dunion and Velden 2004), etc., recent flight-level, dropwindsonde, airborne radar observations collected within the high reflectivity (core) region of intense hurricanes by NOAA WP-3D aircraft indicate that vortex-scale processes have an integral role in the mature storm's inner-core dynamics and thermodynamics. The phenomena include rapid intensification, secondary eyewalls, vortex Rossby wave filamentary structures, vortical hot towers, and eyewall mesovortices (Willoughby et al. 1982, 1985; Black and Willoughby 1992; Montgomery and Kallenbach 1997; Reasor et al. 1999; Hendricks et al. 2004, Montgomery et al. 2006; Schubert et al. 1999; Kossin and Schubert 2001; Braun et al. 2006). In the interests of brevity, only the first two will be summarized here.

Rapid intensification of a moderately intense storm near populated coast lines represents the dreaded "forecaster's nightmare" scenario. Hurricanes Charley (2004), and Wilma (2005) are recent reminders of what is possible. Rapid intensification is clearly a major forecast challenge, and it is unclear whether the HWRF version 1 will be able to predict these events.

The secondary eyewall phenomenon is another important forecast requirement. Secondary eyewalls, and the cycles of weakening and strengthening that accompany them, often occur in category four or five storms. Hurricane forecasters and research meteorologists have long known these to be harbingers of intensity change on time scales between 6 h and 24 h (Willoughby et al. 1982, 1985; Black and Willoughby 1992). The extensive flight-level and microwave satellite observations collected during the 2005 hurricane season indicate that knowledge of the timing and duration of such events can provide critical life-saving information to the hurricane forecaster and emergency manager as a hurricane is threatening landfall.

Most operational models (except the GFDL model) have horizontal resolutions of 30 – 40 km, which is far too coarse to resolve the formation and evolution of secondary eyewalls. Although the GFDL model nominally runs at 1/6 degree horizontal resolution, this is still too coarse to capture these events. The insufficient horizontal resolution employed by these operational models, coupled with their use of convective parameterizations, is a major roadblock in capturing the timing and duration of these intensity change events that depend on vortex-scale processes.

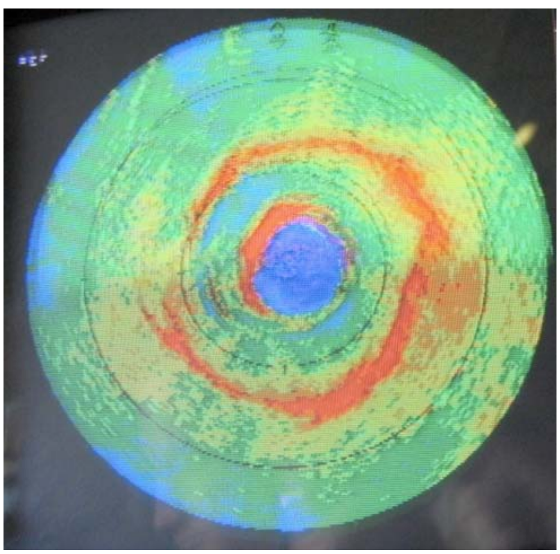


Figure 6.1: Digital photograph of the radar scope of the lower fuselage radar aboard the WP-3D NOAA 42 aircraft on 22 September, 2005, during a research flight into Hurricane Rita during the RAINEX field experiment. Range rings are in twenty nautical mile increments and he warmer colors indicated higher rain rates. The primary (inner) and secondary (outer) eyewall are evident.

The lack of our ability to accurately forecast rapid intensification and secondary eyewalls is compounded by our lack of basic physical understanding of the phenomenon and especially its initiation process. For example, secondary eyewalls may entail primarily internal dynamics (e.g., Willoughby et al. 1984; Terwey and Montgomery 2006) or responses to environmental changes (e.g., Nong and Emanuel 2003; Kuo et al., 2005) is unresolved, but the events do involve modifications in the core of the tropical cyclone. For example, one theory hypothesizes that secondary eyewall formation is an intrinsic non-axisymmetric ‘”eddy flux divergence” associated with the outward propagation and accumulation near a “stagnation radius” of convectively-generated moist vortex Rossby wave filaments that propagate in the radial potential-vorticity waveguide of the azimuthal mean vortex (Montgomery and Kallenbach 1997). If vortex Rossby wave filaments are an integral component in the lifecycle of secondary eyewalls, then accurate intensity forecasts may not be possible until sufficient computational and manpower resources are committed to this problem using 'cloud-resolving' mesoscale numerical models with a horizontal grid spacing of less than 2 km in order to represent an active enstrophy casade around the hurricane core.

The secondary eyewall phenomenon is illustrated by a digital photograph (Fig. 6.1) of the lower fuselage (5 cm) radar scope recorded onboard the WP-3D NOAA 42 during a research mission into Hurricane Rita (2005).

Improved understanding of the role of transport, mixing and coherent vortex structures in hurricane intensity has been the topic of an unprecedented high resolution data set collected from category five Hurricane Isabel (2003) during the CBLAST field campaign (Black et al. 2006) has provided important new insight into the thermomechanics of intense storms (Montgomery et al. 2006; Aberson et al. 2006; Bell and Montgomery 2006). These studies are the first to document the potential existence of a "superintense" hurricane (one that may exceed previously defined maximum potential intensity considerations) whose existence was first predicted via high resolution numerical hurricane simulations (Persing and Montgomery (2003).

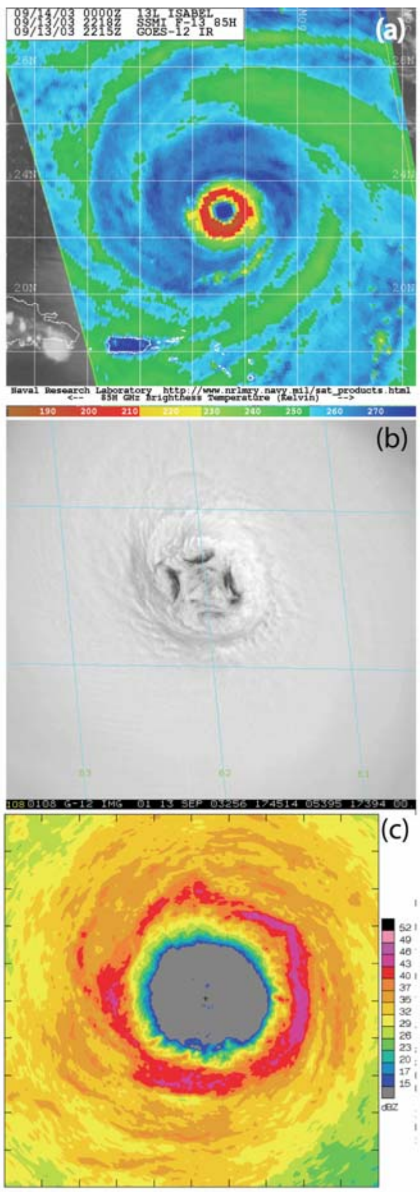


Figure 6.2. Satellite and airborne radar imagery of Hurricane Isabel on 13 September, 2003. (a) SSMI 85 GHz brightness temperature at 2218Z(courtesy of NRL/Monterey) ; (b) Visible image at 1745 UTC from GOES super-rapid-scan operations; and (c) Radar reflectivity (in dBZ) from lower-fuselage (5 cm) radar onboard NOAA aircraft while flying inside the eye at ~2 km altitude. The time of the radar image (1747 UTC) is two minutes after the visible image shown in (b). In (a), (b) and (c) the horizontal scales of the images are approximately 1400 km, 300 km and 180 km, respectively. The mesovortices within the eye in (b) and the pentagonal shape of the high reflectivity in the eyewall in (c) are particularly striking features.

Figure 6.2a shows the nearly circular core of deep convection of Isabel's eyewall at 2218 UTC on 13 September, represented by the cold (red) 85 GHz brightness temperature. Non-axisymmetric structures inside the eye with connecting cloud bands to the eyewall are also apparent in the low-level stratus clouds at 1745 UTC (Fig. 6.2b), along with the appearance of a pentagon of high reflectivity from a NOAA P3 lower fuselage radar image at approximately the same time (Fig. 6.2c). These observations, in conjunction with GOES super rapid-scan animations (not shown), corroborate the existence of coherent mesovortices in the vicinity of the eyewall that have been predicted by high resolution numerical simulations (Schubert et al. 1999; Kossin and Schubert 2001; Persing and Montgomery 2003) and liquid-water laboratory experiments (Montgomery et al. 2002). The mesovortices are believed to be the result of a combined barotropic/baroclinic instability and nonlinear evolution associated with an annulus of potential vorticity near and within the eyewall cloud. The potential vorticity annulus is generated by latent heating and vortex tube stretching in the eyewall.

A two-dimensional analysis of the axisymmetric kinematic and thermodynamic structure of Isabel in the radial-vertical plane has been performed using in situ measurements from flight-level data and eyewall and eye dropwindsondes released from 3 aircraft (two NOAA P-3s and a USAF C-130) flying at different altitudes. Figure 6.3 shows the kinematic and thermodynamic structure of Isabel on 13 September from 1600 – 2300 UTC derived from these GPS dropwindsondes and flight level data.

The maximum average tangential wind (76 m s^{-1}) is located approximately 42 km radius from the center and near 1000 m above the surface. (This wind, by virtue of the averaging required to compute it, is likely comparable to a sustained wind at this level.) The observed sharp tangential wind gradient along the inner edge of the eyewall is consistent with the presence of local Kelvin-Helmholtz instabilities and associated lateral mixing across the eyewall interface. Lowest-level (0-250 m) radial inflow of approximately 20 m s^{-1} located 25 km radius from the center suggests significant penetration of air from the eyewall into the eye. Strong, inflowing air that breaches the eyewall is modified by sea-to-air latent heat flux inside the eye where widespread downdrafts that ordinarily tend to limit the ocean energy gain outside the eyewall do not exist.

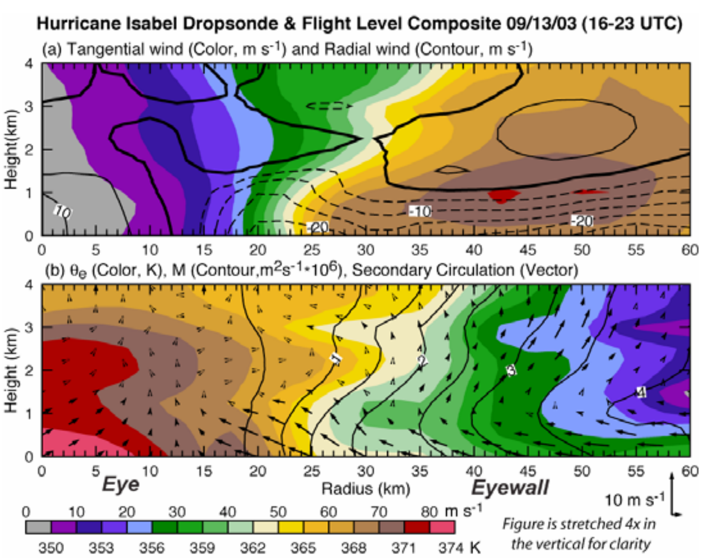


Figure 3. Radius-height azimuthal mean structure derived from GPS dropwindsonde and flight level data from 1600 – 2300 UTC, 13 September, 2003.

Despite the rapid tangential wind speed decrease inside the eye, the low pressure, and significant inflow and convergence near the surface support non-zero and persistent sea-to-air latent heat flux within the eye that tends to maintain a reservoir of high θ_e air, which is consistent with previous studies. The analysis (Fig. 3b) suggests that the high entropy air returns in the outflow above 1 km, as indicated by the outward bulge in the θ_e contours near 2 km altitude. The small outward bulge evident in the analyzed absolute angular momentum near 37 km radius and 2 km altitude provides additional evidence of this exchange, which is consistent with the injection of this high θ_e air into the eyewall. This represents a potential additional energy source to the hurricane heat engine, that may be used by the hurricane to intensify beyond current maximum potential intensity considerations. This mechanism is thought to be operative in other less optimal environmental conditions possessing increased vertical shear and/or reduced sea surface temperatures (Cram et al. 2006). Because of the turbulent nature of the superintensity process, the observational and computational challenges are considerable and only through dedicated observational campaigns such as CBLAST and high-resolution idealized and real-case numerical simulations will a complete understanding of this phenomenon emerge.

6.3 Applied Research and Development Opportunities and Priorities

Applied development refers to the transfer to operations of scientific knowledge/tools/techniques that are currently at hand, and thus are short- and medium-term opportunities.

Perhaps the least understood and most important issues among contemporary challenges to hurricane-intensity forecasting relate to anticipation of the onset of:

- A 12-24-h-long interval of rapid intensification or weakening, and,
- A 6-24-h cycle of eyewall replacement.

Whether these events entail primarily internal dynamics or responses to environmental changes is unresolved, but the events do involve modifications in the core of the tropical cyclone. The gap here lies thus in identification of observationally accessible, telltale precursors of rapid intensification/weakening and eyewall-replacement cycling and this is impeded by uncertainty about the physical processes involved.

Recommendation: **Priority should be given to enhanced support for basic 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 cross the eye wall, and the impact of environmental interactions.**

6.3.1 Medium Term Applied Research Priorities

The HIRWG has already noted the critical need for supporting numerical model development and application at high resolution and its associated data assimilation in improving the forecasts of hurricane structure and intensity. This section addresses other aspects of applied research that may also lead to improvements.

A diagnostic boundary-layer model could provide plausible comprehensive velocity and thermodynamic fields, in the near-surface boundary layer of a mature, quasi-steady hurricane shortly after landfall. Currently, piecemeal data, compiled from multiple sources and tropical cyclones, are fused to form representations of the near-surface flow in a hurricane after landfall; these representations, though utilized for legal, structural, and meteorological purposes are of uncertain credibility.

***Recommendation*: A diagnostic boundary-layer model be considered to guide the integration of piecemeal data and the analysis important surface wind field details after landfall.**

A significant contribution to hurricane-track prediction is being made by application of a poor-man ensemble (consensus)-forecasting procedures. Accordingly, the development of a systematic procedure for the preparation in real time of an ensemble forecast of tropical-cyclone intensity is expected to yield a significant upgrade in predictive accuracy. This improvement is anticipated to be particularly noteworthy for short-term forecasting, say, for times up to 48 hours ahead, for weaker-intensity tropical cyclones: these systems are more responsive to track-determined environmental conditions, and the track forecasts become monotonically less accurate for longer times. The steps to be pursued include the following decision train:

- What tools exist to contribute to an intensity-dedicated ensemble;
- What tools are needed that can contribute to an intensity-dedicated ensemble;
- What input parameter(s) ought to be varied for an ensemble, based on robustness of forecast to uncertainty of assigned value, to be carried out in real time by repeated use of a single forecasting tool; and
- How to fuse, with time-varying weightings based on performance, predictions generated by a single realization each of many different models.

***Recommendation*: Consideration should be given to developing an operational capability to generate ensemble forecasts of the hurricane intensity and to combination of these in an optimal statistical manner, which includes uncertainty estimates.**

6.3.2 Longer Term Applied Research Priorities

Information concerning tropical-cyclone-associated sustained-wind speeds and gust factors on structural scales (~10 m) is desired to guide the design, construction, response, and retrofit of buildings and infrastructure. Currently these are obtained by relatively primitive and coarse-grained simulations.

***Recommendation*: NOAA should investigate improving the capacity to assess very high resolution wind field variations of relevance to structural aerodynamic requirements.**

6.4 Moving from Research to Operations

The NOAA Strategic Plan proposed the formation of testbed centers to facilitate the transition of research results to operational forecast centers. The Joint Hurricane Testbed (JHT) was one of the first such testbeds and has been very successful in transitions of operational products for the National Hurricane Center and hurricane modeling innovations to the NCEP/EMC, either for the operational Geophysical Fluid Dynamics Laboratory hurricane model or the Hurricane Weather and Research Forecast (HWRF) model to be implemented in 2007. Approximately 75 of past projects have been accepted for operations, and another 27 JHT projects are now being tested. Because improved hurricane intensity forecasts are the top JHT priority, many of these projects have directly or indirectly addressed this priority. New research models have recently demonstrated success in forecasting hurricane intensity changes, and indicate that much higher horizontal resolution and more complex physical processes are required.

The funding for JHT has decreased even in view of its success. The JHT is not a proper mechanism for testing completely new hurricane intensity models that have been developed by non-EMC personnel, or testing some aspects of the second generation HWRF model, because the JHT structure and capabilities are not appropriate for this task.

***Recommendation*: JHT funding be restored to previous levels, or higher levels if a significant number of well-qualified proposals continue to be declined for lack of funds for these critical projects.**

***Recommendation:* 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 hurricane forecasting.**

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Possible Sidebars:

1. Saffir-Simpson Scale

2. Graphic showing eye-wall replacement cycle

Appendix 1: Terms of Reference

Background

The National Oceanic and Atmospheric Administration (NOAA) has made substantial progress in recent years improving the accuracy of hurricane track forecasts. These improvements were one of the driving forces behind the decision to extend track forecasts to five days. To date, similar improvements have not been made in hurricane intensity forecasts.

As a result of improved hurricane track forecasts, in the last 50 years there has been a substantial reduction in the number of lives lost. However, there is a significant potential for a large loss of life in densely populated coastal areas if a Saffir-Simpson Scale category 1 or 2 storm suddenly intensifies into a category 4 or 5 storm as hurricane Charlie did last summer.

A goal of NOAA's research and development into tropical cyclones is to understand and describe the physical processes that lead to the extreme winds in a hurricane, and to use this knowledge to develop an integrated hurricane simulation and forecasting system that produces skillful forecast guidance of intensity change in hurricanes striking the United States. The benefits will include better warnings to the public of hurricane strength so appropriate disaster preparedness actions can be completed while minimizing unnecessary preparation costs and evacuations.

Advances in hurricane track forecasting occurred through research that has led to a better understanding of hurricane evolution and interaction with large-scale steering currents, and through continuous development and enhancement of numerical weather prediction modeling systems. Achieving improvements in intensity forecasts is a much more difficult problem, requiring understanding and simulation of the crucial physical and dynamical processes that determine the inner core structure and interactions with the environment. Significant improvements in the simulation and forecasting of hurricane intensity would represent a great leap in our ability to protect life and property from hurricanes.

The NOAA Weather and Water Goal Program Plan designates intensity forecast improvements as a high priority and the National Weather Service Science and Technology Infusion Plan describes the operational goals for intensity forecasts over the next 5-10 years. NOAA has put together a plan to address operational goals, and is developing a new hurricane model using the Weather Research and Forecasting (WRF) model infrastructure in concert with the tropical numerical modeling community. This model will be coupled with ocean and land surface models, which were developed in the academic community. Simultaneously, NOAA is also working closely with NASA, the

National Science Foundation, and the Department of Defense to collect and analyze critical ocean and atmospheric data for the purpose of developing improved model parameterization schemes as well as model forecast verification information.
NOAA also established the Joint Hurricane Testbed (JHT) as a way of accelerating the transition of promising research to operations. On a two-year cycle, this activity funds competitive grants and cooperative institutes to facilitate preparation and testing of promising forecasting techniques and numerical model improvements.

NOAA Science Advisory Board Charge

NOAA has requested the NOAA Science Advisory Board (SAB) to assemble a working group of external experts to conduct a review of NOAA's hurricane intensity research, development, and transition to operations. The working group should consist of not less than eight members whose expertise as a group covers tropical cyclone instrumentation; observations and modeling; atmospheric and ocean dynamics, data assimilation, and modeling; vortex dynamics; fluid mechanics; operational numerical environmental modeling; and forecast operations. The working group should include representation with socio-economic expertise that relates to this problem. The working group members should have the following qualifications:

1. National and international professional recognition;

2. Knowledge of and experience with the science that supports NOAA's tropical cyclone research and operations;

3. Knowledge of and experience with the organization and management of complex mission oriented research and development programs; and

4. No perceived or actual vested interest or conflict of interest that might undermine the credibility of the review.

Hurricane Intensity Research Review Working Group Charge

The Hurricane Intensity Research Review Working Group should conduct an independent review of NOAA's hurricane intensity research, development, and transition to operations. The Working Group should develop findings and recommendations to ensure that this work results in improved operational forecasts. This review is to address NOAA's approach to its research and development efforts in support of improved observations, numerical modeling and operational warnings and forecasts. Rather than continue with incremental improvements in understanding and in intensity forecasts, NOAA seeks advice to help answer fundamental questions on the dynamics and behavior of hurricanes that will lead to significant improvements in forecasting and service to the Nation. This review is to include NOAA's working arrangements with other Federal agencies and the academic community, and the level of effort and resources devoted to this work currently and planned.

Specifically:

Science and Science Planning

1. Is NOAA conducting/sponsoring hurricane intensity research in the right areas?

2. How should NOAA identify relevant new research opportunities? How should innovative and creative perspectives and theories be evaluated, incubated, and tested?

3. How should NOAA involve the larger research community in identifying promising lines of investigation?

4. Who are the NOAA tropical cyclone research and development customers?

5. Are the needs of these customers considered in shaping the research effort (for example, defining hurricane intensity metrics) and how can NOAA improve the process?

6. What formal procedures, if any, exist for joint planning with other agencies (e.g., U.S. Weather Research Program) and academia and how can they be improved?

Transition of Research to Operations

1. How should NOAA ensure it derives the maximum benefit from tropical cyclone research and development conducted by it and others?

2. Does the JHT adequately serve to link NOAA operational components (e.g., Environmental Modeling Center and Tropical Prediction Center) to NOAA research and the larger research community?

3. What operational needs are not being addressed by NOAA's research and development activities?

Resource Planning

1. Are current and planned hurricane intensity R&D resources (financial, institutional, and intellectual) adequate to make significant advances in improving hurricane intensity forecasts?

2. Are current and planned hurricane intensity R&D resources consistent with NOAA's plans, goals, and objectives as articulated in the NOAA Strategic Plan, NOAA 5-Year

Research Plan, NOAA Goal and Program Plans, and science and technology infusion plans?

3. What is provided in the way of human resources development (recruitment, rewards, training)? Is it enough? Too much?

Term

The working group will carry out this review in approximately nine months once the working group is convened. The working group will prepare a preliminary report of its analysis and findings within six months of being established, and a final report, including recommendations, will be completed within nine months. The working group will be dissolved after completing any follow-on request regarding the final report by the SAB.

Appendix 2: HIRWG Membership

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Appendix 3: Timeline

Appendix 4: List of Presentations Made to the HIRWG

Appendix 5: Definitions and Terms

Appendix 6: Summary of Recommendations