Majority Report

National Oceanic and Atmospheric Administration

Science Advisory Board

Hurricane Intensity Research Working Group

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1 Executive Summary

1.1 Background

Over the last three decades, research and development has resulted in substantial improvements in skill in forecasting of hurricane track. Unfortunately, parallel improvements in forecasting skill for hurricane intensity and structure have been limited. In particular, rapid intensification and decay of hurricane-strength storms remain poorly forecast. Following the close of the 2004 hurricane season, NOAA management discussed with the NOAA Science Advisory Board (SAB) the need to improve National Weather Service forecasters' skill in forecasting intensity and structure, and in particular, rapid changes in intensity in hurricane-strength storms. The SAB subsequently constituted the Hurricane Intensity Research Working Group (HIRWG) and charged it with:

- Independently assessing the "state of the science" and current research and development (R&D) activities in NOAA and elsewhere with respect to hurricane intensity; and then

- Recommending an agenda of R&D activities that will lead to an improved understanding of the processes that determine hurricane intensity and the timely transfer of that understanding to operations.

In responding to this charge, the HIRWG meet or talked by telephone with a broad cross-section of individuals active in hurricane forecasting and research, many of whom provided scientific and technical materials for the HIRWG's consideration. It also solicited input from the SAB and public comment on a preliminary draft of this report. All input was considered in preparing the HIRWG majority's final report.

Beginning in late February, one HIRWG member declined to participate further. Also, as the HIRWG was beginning preparation of its final report, two HIRWG members elected to withdraw from further participation and to prepare a minority report. This minority report has been provided separately by those two members.

In their report, the HIRWG majority of 7 individuals has stated a possible overarching goal and made 29 recommendations that are discussed in detail in the body of this report. These cover a wide range of activities that would improve forecast skill for hurricane intensity and utilize that improved ability for societal benefits.

1.2 An Overarching Goal and the 10 Highest Priority Recommendations

This section states a possible overarching goal and highlights 10 recommendations that the HIRWG majority considers to be of the highest priority and to which it has assigned short or medium timeframes for accomplishment of the recommended action[1].

As overarching goal for NOAA R&D in improving the skill for intensity forecasting, HIRWG recommends:

To reduce the error in 48-hour intensity forecasts for hurricane-strength storms 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, and decay and reintensification cycles.

HIRWG finds that the above-stated goal can be achieved by focusing research on the inner core of the hurricane using

- Advanced Numerical Weather Prediction Systems with…
- Novel Methods for Data Assimilation founded on…
- Improved Observations of the Hurricane and its Environment and…
- Focused Applied Research and Development.

A program to achieve this goal and provide maximum public benefit will require organizational changes that attain…

- Critical Mass, and accelerate…
- Transfer of Research Results to Operations.

To provide the foundation necessary to attain this goal, the HIRWG makes the following overarching recommendation:

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

[1] *Short term* as 1 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;

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.

1.2.1 Application of Advanced Numerical Weather Prediction Systems

The HIRWG was presented with strong evidence that numerical models must have horizontal grid spacing approaching 1 km to capture phenomena and processes in the core region that are important to accurate prediction of rapid intensification and eyewall cycles, which will be necessary for improved intensity forecasts of hurricane-stage storms. Advancements are also required in prediction of the physical processes, including the atmospheric boundary layer, air-sea interface processes including sea spray, and interactive coupling between the ocean and the atmosphere on the spatial scales of the hurricane inner core.

Specific Recommendations:

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

- **(Medium-term) NOAA should reprioritize existing or acquire the necessary computing system capability to produce approximately 1-km-resolution hurricane forecasts.**

1.2.2 Novel Methods for Data Assimilation

A surrogate for real initial data in hurricane forecast models is the technique of using a “bogus” vortex, but this is only an intermediate step for hurricane intensity forecasting. The HIRWG finds that a state-of-the-science data-assimilation system is and will continue to be a crucial element in any advanced numerical weather prediction system as it allows useful initial data to be extracted from nontraditional observations, such as radar, aircraft, satellite, dropsonde, etc.

Specific Recommendations:

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

- **(Short-term) Airborne and surface-based radars offer the best opportunity to observe mesoscale fields in the inner core region but full realization of their potential requires real time assimilation into models. A focused**

program aimed at assimilating radar data into HWRF is recommended, with the goal of operational testing in 2007.

1.2.3 Improved Observations of the Hurricane and its Environment

There are numerous observing systems already in use for monitoring hurricanes, each with its own positive attributes and drawbacks. Combining a broad range of atmospheric and oceanic 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. 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. In addition, there are promising new technologies in-hand (Stepped Frequency Microwave Radiometer) and on the horizon (Unmanned Aerial Systems; radar on the Gulfsteam-IV).

Specific Recommendations:

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

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

1.2.4 Focused Applied Research and Development

Adoption of high-resolution, coupled models will lead to improved predictions of intensity change over the present models, but only if fundamental aspects of rapid intensification, decay, re-intensification cycles, and rapid decay are represented in the prediction model. Unfortunately, many of these fundamental aspects are not well understood.

Specific Recommendation:

- **(Short- to medium-term) Priority should be given to enhanced support for research to advance understanding of phenomena related to predictability of rapid intensification and secondary eyewall phenomena. This should include**

investigations of core processes such as heat and momentum exchanges with the surface and across the eyewall and the impact of atmospheric and oceanic interactions.

1.2.5 Attaining Critical Mass

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 of the vortex core and boundary layer is seen as key to achieving our goal. Yet, with the redirection of the Geophysical Fluid Dynamics Laboratory (GFDL), the limited number of development and implementation staff at the National Centers for Environmental Prediction (NCEP), and lack of modeling capability currently at Hurricane Research Division (HRD), NOAA presently 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 the National Center for Atmospheric Research (NCAR) and the Naval Research Laboratory (NRL) that complements the NCEP expertise, but the coordination between these research and operational activities is deficient, and should be substantially improved.

Specific Recommendation:

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

1.2.6 Transfer of Research Results to Operations

A major consideration should be the acceleration of the transfer of research and development to operational forecasting and dissemination of hurricane information to the public. Specifically, how to effectively communicate the inherent uncertainties in hurricane intensity forecasts is acknowledged to be a difficult problem.

Specific Recommendation:

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

2 Introduction

2.1 Motivation for this Report

Over the last three decades, research and development has resulted in substantial improvements in skill in forecasting of hurricane track (Fig. 1). This is one of the great success stories of weather forecasting.

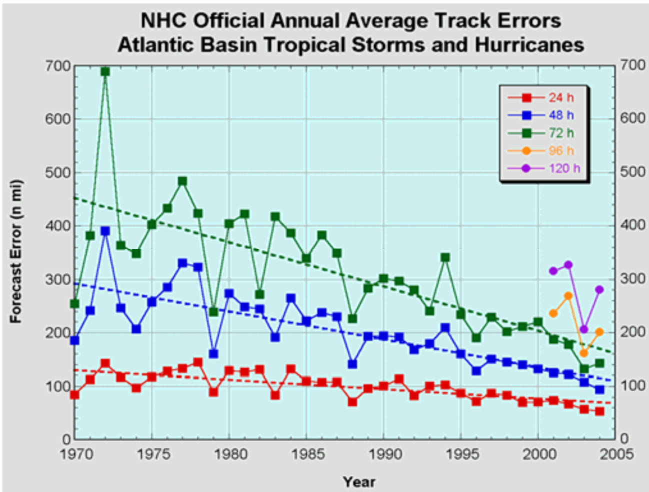

Figure 2.1. Improvements in annual track errors since 1970.

Unfortunately, parallel improvements in forecasting skill for hurricane intensity and structure have been limited. In particular, rapid intensification and decay remain poorly forecast. "Surprises", or unforecasted rapid intensity changes, are the result. For example, recent surprises have included:

- Charley – 2004 – rapid intensification just before landfall
- Katrina – 2005 – rapid weakening just before landfall
- Wilma – 2005 – rapid intensification to a record minimum central pressure

This lack of skill to accurately forecast rapid changes in hurricane-strength storms leads to conservative over-warning, with significant economic consequences and reduced willingness by the public to take action when a real threat emerges.

Following Hurricane Charley, NOAA management discussed with the NOAA Science Advisory Board (SAB) what might be done to improve the NWS forecasters' skill in forecasting intensity and structure, and in particular, rapid changes in intensity in hurricane-strength storms. The SAB subsequently constituted the Hurricane Intensity Research Working Group (HIRWG) and charged it with:

- Independently assessing the “state of the science” and current research and development (R&D) activities in NOAA and elsewhere with respect to hurricane intensity; and then

- Recommending an agenda of R&D activities that will lead to an improved understanding of the processes that determine hurricane intensity and the timely transfer of that understanding to operations.

The detailed HIRWG terms of reference appear in Appendix 1. The membership of the HIRWG appears in Appendix 2.

The HIRWG began its task in September 2005 with a goal of submitting a near-final report for consideration at the summer 2006 meeting of the SAB. The HIRWG met formally four times, conducted numerous teleconferences among its members and with outside experts, and had members attend a number of professional and scientific meetings. The time line of HIRWG activities is given in Appendix 3; meeting agendas are given in Appendix 4. These activities provided the HIRWG opportunities to have discussions with federal and academic scientists, operational meteorologists, and senior federal managers. The professional and scientific meetings allowed members of the HIRWG to hear the most recent research results and plans from the wider community, and to interact with national and international colleagues.

The HIRWG prepared a preliminary draft of its report and submitted it for review by the SAB. This review was accomplished at the SAB’s March 2006 meeting. The feedback on the preliminary report received from the SAB helped shape this final report.

Further, the HIRWG sought public comment on the preliminary draft (somewhat revised to reflect the feedback from the SAB) in May and June. This was accomplished by posting the preliminary draft to the SAB web site and publishing an announcement of a 30-day comment period in the Federal Register. Eleven comments were received during the 30-day period. In addition, one comment was received one week after the formal close of the comment period. All twelve comments were examined in detail by the HIRWG. In several cases, the comments significantly influenced the discussions and recommendations contained in the final report. As a result of continued work by the HIRWG and consideration of the comments received from both the SAB and the public on the preliminary draft, the final report is significantly different in content from the preliminary draft.

From late February on, one HIRWG member (Webster) ceased to participate. Further, as the preliminary draft was being posted for public comment, two HIRWG members (Baum and Fendell) elected to withdraw from further participation and to prepare a separate minority report. This minority report has been provided separately by those two members.

2.2 The Majority Report

Sections 1 through 10 constitute the majority report from 7 (Chen, Elsberry, Holland, Krishnamurti, Montgomery, Rotunno, Snow) of the original 10 HIRWG members. It provides 29 recommendations covering a broad range of research and development topics, ranging from basic scientific explorations and advancing numerical modeling to societal impacts. Implementation of these recommendations will improve skill in forecasting hurricane intensity and structure in hurricane-strength storms, and increase our ability to utilize that skill for societal benefit.

Ten recommendations of particular importance to attaining the overarching goal are highlighted in shaded boxes for emphasis. The HIRWG considers these ten to be of the highest priority, and has assigned short or medium timeframes for their accomplishment.

A thread connecting many of these recommendations is the development of mesoscale models capable of resolving important details in the eye-wall structure. A schematic illustrating the importance of such a model and its relationship to other recommended activities is shown in Fig. 2.

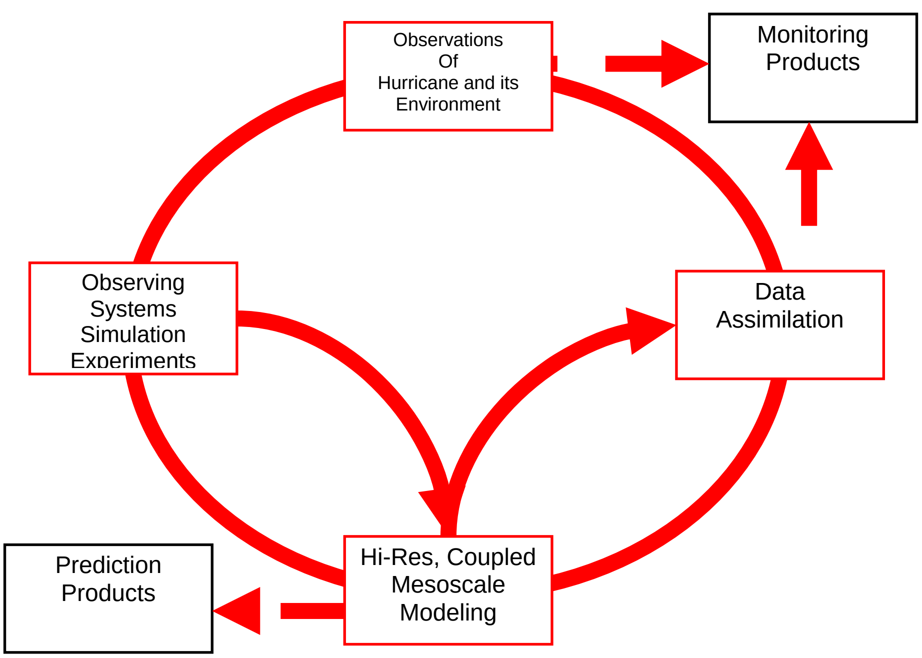

Figure 2.2. The central role of research and development in addressing hurricane forecast improvements.

Development of a model with the capabilities recommended in this report will require research on a wide range of atmospheric and oceanic topics. As the above illustration suggests, this model will serve as a tool for research and demonstrating increased skill in forecasting hurricane intensity.

The majority report is organized as follows:

- A statement of the problem and the challenge of intensity and structure forecasting are presented in Section 3.
- Section 4 addresses the highest priority numerical modeling aspects, with a discussion of current operational and representative research models, and establishes the need for advanced high-resolution modeling;
- Section 5 describes the critical data assimilation requirements necessary to incorporate the observations near the storm center, and especially the unique radar data from NOAA aircraft;
- Key atmospheric and oceanic observation systems are addressed in Section 6. This section highlights the importance of Observing System Simulation Experiments (OSSEs) for determining the best mix of observations, together with select major observing systems: Satellite, Manned Aircraft, Unmanned Aerial Systems, Surface, Oceanic, Land-based Radar, and Balloons and Rawinsondes;
- Research requirements related to understanding of key problems in intensity change are described in Section 7;
- The need to attain a critical mass of researchers working collaboratively on the hurricane problem is described in Section 8;
- The ongoing challenge of accelerating the transfer of research to operations is addressed in Section 9;
- A number of important issues and opportunities peripheral to HIRWG charge are described in Section 10, including some that will lead to the public receiving greater benefit from the improved skill in hurricane intensity forecasts;
- Finally, salient details on the HIRWG terms of reference, HIRWG membership, timeline, meeting agendas, definitions and terms, and a summary of observing systems are presented in Appendices 2 - 7.

2.3 Overarching Goal – Majority Report

As a result of its assessment of the “state of the science” and review of current activities in the hurricane research community, the HIRWG is enthusiastic about the possibilities for improving the forecast skill for hurricane intensity and structure, especially in the case of major hurricanes. The HIRWG accordingly recommends that NOAA adopt the following overarching goal for its *research* efforts in this area:

To reduce the error in 48-hour intensity forecasts for hurricane-strength storms 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, and decay and reintensification cycles.

The HIRWG recognizes that this is an ambitious goal, but considers it attainable if resources are made available and properly allocated, and the full hurricane research community – universities, private sector, and government at all levels -- is engaged. The

HIRWG finds that above-stated goal can be attained by focusing research on the inner core of the hurricane using

- ***Advanced Numerical Weather Prediction Systems*** with…
- ***Novel Methods for Data Assimilation*** founded on…
- ***Improved Observations of the Hurricane and its Environment*** and…
- ***Focused Applied Research and Development***.

It is emphasized that attainment of this goal will require significant improvement over current understanding of the detailed structure and life cycle of a hurricane. The HIRWG sees this goal being satisfied with a demonstration by NHC forecasters of greatly increased skill in forecasting the evolution of intensity and structure in hurricane-strength storms.

2.4 Definitions

The National Hurricane Center (NHC) definition of "intensity" is the maximum 1-minute-sustained 10-m-height winds in the core of the storm. It provides an easily grasped measure of storm strength. However, this quantity 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.

"Structure" refers to the three-dimensional distribution of winds in the storm, i.e., to the isotach field. For many applications, such as detailed prediction of storm surge or the expected area of damage to infrastructure, accurate prediction of the distribution of the low-level wind field is essential.

The 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 33 kt;
- Tropical Storm: maximum winds between 34 and 63 kt;
- Hurricane: maximum winds greater than 63 kt.

Hurricane intensities are further subdivided into five categories following 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 96-113 kt with storm surge of 9-12 ft
- Category 4: maximum winds 114-135 kt with storm surge of 13-18 ft
- Category 5: maximum winds >135 kt with storm surge of >18 ft

"Structure" and "intensity" are only loosely coupled. Hurricane Charley was a strong but very compact hurricane whereas Hurricane Katrina was equally strong but much larger in horizontal extent.

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In this report, frequent reference will be made to "research" and "development", sometimes together (as in R&D), sometimes separately. The distinction between these two activities is important to understanding some of the recommendations made here. For present purposes, take

- *Research* to be the seeking of new knowledge and understanding about nature, including the creation of specialized tools and techniques for such purposes; and

- *Development* to be the converting of existing scientific knowledge, tools, and techniques into operational tools and techniques that produce improved products and services.

In NOAA, basic and applied research and early stage development work is usually carried on in one of the laboratories overseen by the Office of Oceanic and Atmospheric Research (OAR). Relevant laboratories here are the Geophysical Fluid Dynamics Laboratory (GFDL), located in Princeton, NJ, and the Hurricane Research Division (HRD) of the Atlantic Oceanographic and Meteorological Laboratory (AOML), located in Miami, FL. Some applied research and most development work is done in elements of the National Weather Service (NWS), in particular, the National Centers for Environmental Predictions (NCEP) and the co-located National Hurricane Center (NHC)/Tropical Prediction Center (TPC). NOAA also maintains critical supporting facilities such as satellite observing systems, an Aircraft Operations Center, networks of land-based radars and surface observing systems, and a variety of coastal and ocean buoys.

NOAA also relies on obtaining the results from basic and some applied research carried out by other federal agencies, notably the National Aeronautics and Space Administration (NASA), the National Science Foundation (NSF), and the U.S. Navy's Office of Naval Research (ONR), and by the academic community, including universities and the National Center for Atmospheric Research (NCAR).

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In some cases, the HIRWG has provided rough estimates of how quickly some research efforts might be expected to produce results that positively impact forecast operations. With the overall planning horizon set to five years, the following definitions were made:

- *Short term* as 1 to 2 years; having potential for impact in the 2007 hurricane season if activity started in Fall 2006, but with little impact on the federal budget process; and

- *Medium term* as 2-5 years; having potential for impact in the 2009 hurricane season; does impact future budgets.

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Hurricane research as a discipline uses many acronyms. A set of acronyms used in this report and their definitions is provided in Appendix 5.

2.5 Acknowledgements

The Chair, on behalf of the Working Group, thanks the following individuals for their efforts in supporting the HIRWG in its work. Roger Pierce, aided by SAB staff Mike Uhart, Cynthia Decker, and Kristen Laursen, provided exceptional administrative and logistic services to the Working Group. Frank Marks of HRD provided valuable assistance and insights. SAB Chair Len Pietrafesa provided excellent advice and assistance with respect to a number of challenging management issues.

The Working Group also thanks the many presenters from the federal government and the academic community who contributed their viewpoints and materials for the HIRWG to consider. The Working Group acknowledges the extra efforts made by Shuyi Chen of the Rosenstiel School, University of Miami, in providing images and detailed comments on recent research by her and her colleagues.

The Chair thanks Kevin Kloesel of the University of Oklahoma for yeoman assistance in the editing and proofreading of a long succession of drafts of the majority report.

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

3.1 Status of Intensity Understanding and Forecasting

As is recognized by NOAA's formation of the HIRWG, there are deficiencies in both understanding and forecasting of hurricane intensity and structure. However, there have been advances in understanding 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; Black et al. 2006, Montgomery et al. 2006);
- Recognition of internal processes, such as vortex Rossby waves, sub-vortex scale structures, secondary eyewalls and eyewall-replacement cycles (Willoughby et al. 1982, Montgomery and Kallenbach 1997, Schubert et al. 1999, Montgomery et al. 2002, Braun et al. 2006);
- 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 1986, Persing and Montgomery 2003, Chen 2006b); and,
- Description of the potential impacts of the near environment, including upper troughs and interactions with nearby weather systems (Montgomery and Farrell 1993, Molinari and Vollaro 2000, Davis and Bosart 2001, Hendricks et al. 2004)

Thus far, the above-cited advances in knowledge have not translated into the desired increased skill in hurricane intensity 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 (Elsberry et al. 2006). These guidance products are largely simple statistical and climatological techniques, and none are able to consistently forecast intensity, or rapid changes of intensity in hurricane-strength storms. The 48-hour forecasts of maximum intensity (time of greatest potential damage) are *consistently* 20 kt (one Saffir-Simpson category) too low, a discrepancy that fails to meet the National Weather Service goal for this quantity. Preparing for storms that are under forecast leads to a myriad of costly impacts, 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 predict rapid intensity changes in hurricanes.

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

- Lack of understanding (and observations) of the atmospheric and oceanic processes that lead to hurricane intensity changes. These intensity-change

processes are complex, and because they occur in the region with the highest winds and waves, they are very difficult to observe;
- Inadequate intensity-forecast techniques. While 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 skill at forecasting hurricane intensity or structure; and
- Inadequate assimilation of available observations into the forecast process.

The current situation has some similarity to that for hurricane track forecasting three decades ago. Subsequently, 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.

Note, however, that predicting track is much more dependent on modeling the atmospheric conditions *around* the vortex. Predicting intensity depends on a wider variety of factors, including not only the surrounding atmospheric conditions, but also the internal details of the vortex, the adjacent oceanic conditions, and the interactions among each of these factors.

Two noteworthy recent undertakings that show promise in addressing this complex set of issues 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. 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 of hurricane intensity changes, as well as testing future intensity forecast techniques.

The HIRWG regards focused research and development, conducted in a coordinated manner, under bold national leadership, as providing considerable promise for future improvements in skill of hurricane intensity forecasting. Specifically, based on its assessment of past and current research, the HIRWG believes that a 10 kt improvement in 48-hour intensity forecasts of hurricane-strength storms can be achieved in 5 years by the application of advanced numerical models, novel methods of data assimilation, and improved observations through a focused applied research and development program.

3.2 Key Research Issues to Address Forecast Needs

A series of thematic research workshops were held under the auspices of the U.S. Weather Research Program (USWRP) from 1997-2002, with the goal of identifying key research issues and directions. These workshops resulted in a series of reports, among them being the Prospectus Development Team (PDT)-5 report (Marks and Shay 1998).

The key research issues brought before the HIRWG by the NHC on current priority needs have substantial overlap with those identified in the PDT-5 report, 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 USWRP effort, including support for the Joint Hurricane Testbed and the development of the Hurricane Weather Research and Forecast (HWRF) model.

However, recent hurricane events, as well as findings of the HIRWG, confirm that there is still little significant progress being made in 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 stated high priority for many, but allocation of human and financial resources commensurate with the complexity of problem has not followed;
- While there is a broad range of activities – observational, R&D, technology transfer, operational – being conducted inside and outside NOAA, the agency is not providing national leadership in this area; and
- The interconnections, coordination and collaboration among related activities across agencies and outside of the government range from poor to average, and there is a tendency towards fragmentation rather than coordination.

However, recent research results that provide a better understanding of the intensity problem are a cause for optimism, and these are addressed in the following sections. To address the lack of progress in this area and take advantage of recent research, the HIRWG makes the following recommendation.

Recommendation 1: (Short- and medium-term) NOAA should allocate sufficient resources and provide national leadership to enable the high-priority research-and-development activities 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 Application of Advanced Numerical Weather Prediction Systems

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

- The requirement for local high-resolution[2] and sophisticated physical parameterizations to enable explicit prediction of salient details of the hurricane core, a recommendation of previous national review panels (e.g., Marks and Shay 1998);
- The assessment using high-resolution observations and high-resolution models of the predictability of the hurricane core features known to be associated with marked intensity cycles;
- The partitioning of available computer power between deterministic forecasts at high resolution and ensemble forecasts at lower resolution, given the limits of current and future NOAA computing capacity.

The HIRWG considers that major improvements in hurricane intensity and structure forecasting first requires adoption of high-resolution numerical modeling of the hurricane core with subsequent evaluation of the forecast predictability. Ideally, all predictions should be done by ensembles at high resolution, but considerations of available computing power indicate the need for an alternate strategy. The HIRWG also suggests an assessment of the optimal combination of high-resolution deterministic models and ensembles of forecasts with coarser resolution. We particularly note the use of lower resolution ensemble modeling for probabilistic forecasts and extended range predictions. Even this alternate strategy is likely to require significantly enhanced computing and human resources.

In particular, the current standard hurricane computing cycle at NCEP may be sufficient to support good quality-track forecasting. However, it is not adequate to support high-resolution modeling of the hurricane intensity and structure, which are needed to accurately predict collateral effects such as accumulated precipitation, storm surge, ocean waves, interaction with coastal topography, and tornadoes. Moreover, the staff and resources required to maintain and upgrade the operational computer models is too small given the complexity of the tasks.

While 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.

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[2] 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.

4.1 Hurricane Models

4.1.1 Operational Hurricane Models at the National Centers for Environmental Prediction (NCEP)

In the late 1990s, US Weather Research Program (USWRP)-supported scientists at Environmental Modeling Center (EMC) upgraded the operational NCEP hurricane modeling capabilities to include a better depiction of the hurricane core circulation, a more detailed description of the hurricane's larger-scale environment through advanced use of satellite data and dropsondes, and improved model physics. Despite the progress made in track prediction, the operational model suite has made comparatively little headway in predicting how strong a hurricane will become and how rapidly a hurricane might intensify or decay. A summary of the NCEP operational hurricane model suite follows.

Global Forecast System (GFS): Supported by the Global Data Assimilation System (GDAS), NCEP's GFS atmospheric model is run at a horizontal resolution of spectral triangular 382 (T382); 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 each day out to 16 days. 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 for that purpose. Its major role in hurricane intensity forecasting is to provide boundary conditions for the specialized hurricane models.

Geophysical Fluid Dynamics Laboratory (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 42 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 skill.

As shown in Fig. 4.1, the GFDL results over the past five years for forecasting hurricane 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 HIRWG 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 to resolve physical processes in the vicinity of the eyewall region of the hurricane.

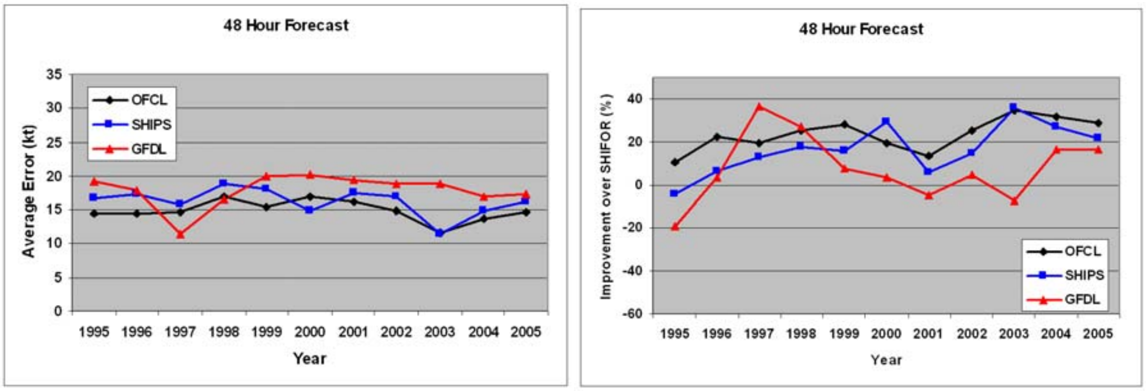

Figure 4.1. GFDL intensity forecast trend since 1995 for the critical 48 h forecast period, compared to the SHIPS statistical technique and the NHC forecasts (OFCL). The left panel is the actual errors and the right panel shows the skill relative to the SHIFOR statistical technique. Provided by Mark Demaria (pc 2006).

The HIRWG was also presented with evidence that the GFDL coupled ocean-hurricane model does not have skill in forecasting intensity changes over the ocean. This evidence suggests fundamental issues remain in ocean modeling appropriate for hurricanes, and suggests a need for ocean observations for validating coupled ocean models.

Hurricane Weather Research and Forecast (HWRF) Model: The HWRF is being developed at NCEP and is proposed for operational hurricane forecasts starting in the year 2007. The HWRF model began as a uniform-mesh prototype system, and a movable nested grid with inner-nest resolution of 9 km was installed and tested at NCEP during the 2004 and 2005 seasons. This system includes the so-called Nonhydrostatic Mesoscale Model (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. Until the HWFR becomes the next-generation hurricane model, the GFDL model will be kept in operation. The panel is impressed with the progress made in the design of HWRF that currently includes many state of the art features such as repeated calls on physical parameterizations, coupling with a high resolution ocean model, two way interactive nesting, multiple nesting, surface-state model for the PBL, design of the synthetic vortex and microphysical parameterizations. The HIRWG supports this HWRF initiative but recognizes that the design of the initiative was limited by the available budget and access to computing power. In particular, inadequate staff is allocated to this important function and the interactions with the external research community in this development have been limited.

The HIRWG has come to appreciate the care that needs to be exercised by EMC for model acceptance of a new model for operational implementation. The HIRWG also notes that this extreme care taken in model acceptance also acts as an obstacle to the rapid infusion of new models and techniques and the participation of outside parties.

Recommendation 2: The planned HWRF Version 1 should be implemented in a timely manner and with the best possible features; the HIRWG considers that this implementation will necessitate enhanced human and financial resources in 2006 and

in subsequent years for development of the next-generation HWRF in conjunction with the external research community.

4.1.2 Hurricane Research Models

The HIRWG reviewed results from a number of research modeling efforts. Two are described here in detail to illustrate the state-of-the-art in this area.

NCAR Advanced Research WRF Model (ARW): The USWRP invested in the Weather and Research Forecast (WRF) model development as a means to more effectively and efficiently transfer 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 original USWRP goal of developing a new community model. The ARW model has very high level conserving properties, multiple physics options, and is built into a software architecture that allows 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 three-dimensional variational (3DVar) and Ensemble Kalman Filter (EnKF) data assimilation systems and a four-dimensional variational (4DVar) data assimilation system will be operational with the U.S. Air Force in 2008.

> **NOTE:** For the NCAR-WRF hurricane forecast model with a 12-km outer nest and a 4-km inner nest, a 3-day forecast takes 5 to 10 h running on 128 IBM Power 4 processors. We note that this computing configuration is comparable to NCEP's computer as of last year.
>
> NCAR WRF domains: 12 km nest: 460x351x35 ,
> 4 km nest: 316x310x35 (grid points)

University of Miami/RSMAS Coupled Atmosphere-Wave-Ocean Model: A fully coupled atmosphere-wave-ocean modeling system was developed at the Rosenstiel School of the University of Miami for hurricane research and prediction. The modeling system includes three model components, the atmospheric (MM5 and WRF), surface wave (WAVEWATCH III), and ocean circulation (HYCOM and 3DPWP) models. The coupled atmosphere-wave-ocean model simulations of hurricanes have been evaluated and validated using the CBLAST observations (Chen et al. 2006a). Both MM5 and WRF contain vortex-following, 2-way nested grids, developed at UM/RSMAS, that allows the model to be integrated for 5 days or longer at very high resolution (~1 km) in the innermost domain. The vortex-following nested grid system is described in Tenerelli and Chen (2001) and Chen and Tenerelli (2006). MM5 and WRF may be run in both coupled and uncoupled mode. During the RAINEX field program in 2005, mini-ensembles of high-resolution MM5 and WRF forecasts were created at UM/RSMAS and NCAR in real-time to aid the aircraft mission planning and post-mission data analysis (Houze et al. 2006 and Chen 2006). The high-resolution, multi-nested grid (15, 5, 1.67 km) MM5 and WRF forecasts were computed on a 10-node, dual-core (4 processors on each node) Linux cluster at UM/RSMAS.

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

NOTE: For Dr. Chen's MM5 hurricane forecast model with 3 nests, a 3-day run takes 24h on a 4-processor Linux box

Miami MM5 domains: 15 km nest: 300x200x28,
5 km nest: 121x121x28,
1.67km nest: 190x190x28 (grid points)

(Note the MM5 domains are considerably smaller than the NCAR-WRF model runs.)

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 hurricane;
- Interaction with the upper ocean including surface energy exchanges and forced upwelling and cooling.

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 structure of the eye/eyewall region be resolved. Since a typical hurricane eye is approximately 40-60 km across, this requires a grid spacing of at least 5 km to resolve the primary vortex. Recent research has emphasized the importance of coherent structures within the eyewall region (e.g., vortex Rossby waves, sub-vortex scale convective vortices and related mixing processes of angular momentum and heat, etc.), in the overall intensification process. To adequately represent this mixture of wave and convective turbulence processes a substantially smaller horizontal grid spacing of approximately 1 – 2 km is believed to be necessary using only cloud physics and sub-grid scale closure parameterizations.

As a first example, NCAR has been running their ARW model in real-time simulations (6 hours of CPU time producing a forecast of 72 hours) 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. 4.2), in a limited test for expected landfall within 72 hours, indicates that the 4 km version of the ARW has similar skill as other techniques for the first 36-48 hours and then provides substantial improvement over other techniques to the ending time of their runs. Figure 4.2 leads to two important inferences:

- The lack of observations and data assimilation suitable for integrating hurricane models at 4-km resolution 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.

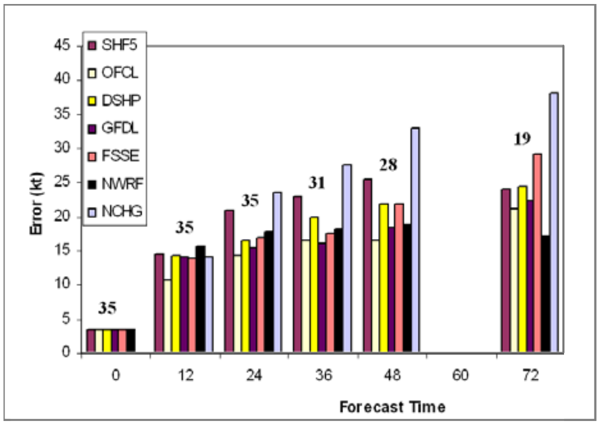

Figure 4.2: Homogeneous comparison of the 4 km NCAR WRF with a number of other forecast techniques for real-time predictions conducted in the 2005 hurricane season. The numbers above each time group indicate the number of forecasts. SHF5 and DSHP are statistical techniques, OFCL is the NHC forecast, GFDL is the GFDL model, FSSE is the Florida super ensemble, NWRF is the NCAR WRF, and NCHG is no change in intensity

As a second example, the HIRWG was presented with evidence of the importance of higher resolution by Shuyi Chen (University of Miami). This took the form of detailed simulations of the evolution of the intensity and structure of several recent major hurricanes (Frances - 2004; Katrina, Rita - 2005), as illustrated in the following figures.

In a presentation to the HIRWG, Chen's modeling results showed a remarkable improvement in skill for both the MM5 and WRF model prediction of intensity in Hurricane Katrina when the grid resolution was increased to below 2 km (Fig. 4.3).

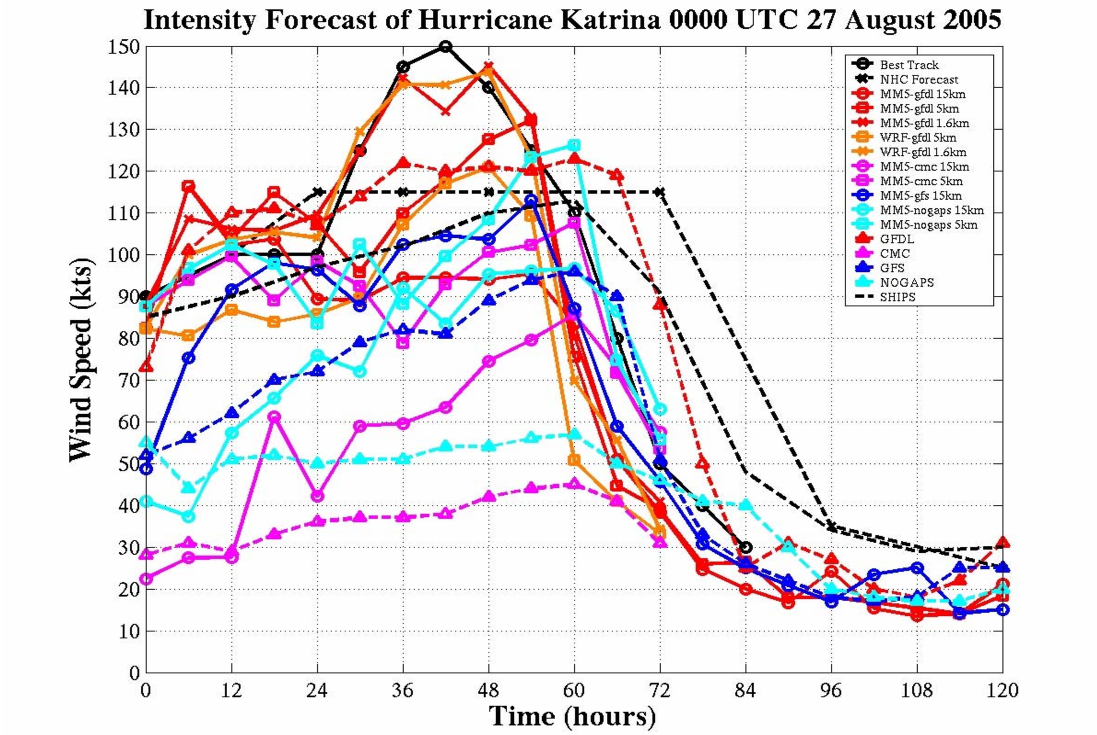

Figure 4.3. Mini-ensemble of MM5 (red solid lines) and WRF (brown solid lines) forecasts of the maximum wind speed in Hurricane Katrina at 15, 5, and 1.67 km resolutions using various large-scale model forecast fields as lateral boundary conditions. The large-scale model forecasts are in dashed lines (GFS-blue, CMC-magenta, NOGAPS-cyan, and GFDL-red). The models are initialized at 0000 UTC 27 August 2005.

Figure 4.3 well illustrates the impact of increasingly finer resolution on improving skill in predicting maximum wind speed. For the models considered, the effect is somewhat independent of other model details.

Further, Chen's high-resolution model forecasts were able to resolve the strong gradients in rain and wind fields near the eyewall and the eyewall contraction that is critical in an intensifying storm. As an example, Fig. 4.4a shows that the 1.67-km forecast captured the formation of the concentric eyewalls and an eyewall replacement in Hurricane Rita as observed (Houze et al. 2006), whereas the 5-km forecast did not (Chen 2006). Snapshot images in these two time sequences, shown in Fig. 4.4b, illustrate that the 1.67-km forecast resolved the concentric eyewalls while the 5-km forecast did not.

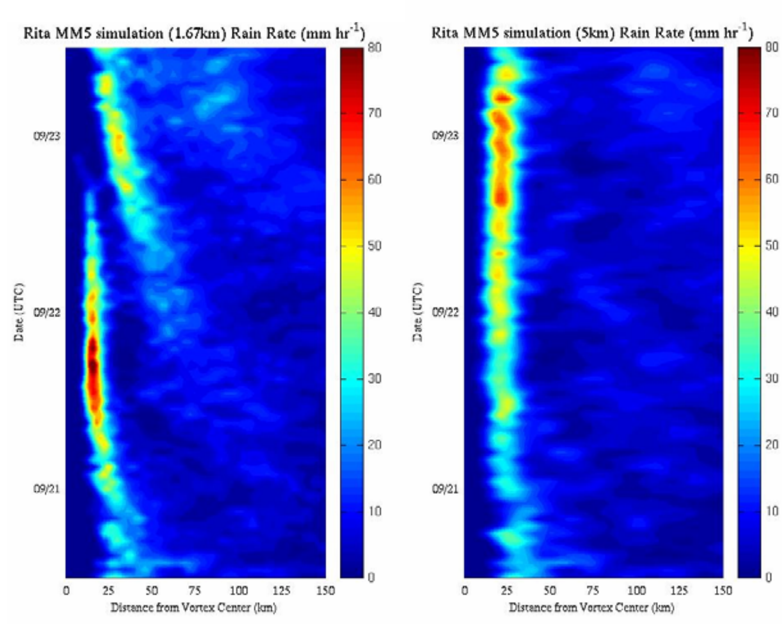

Figure 4.4a. Time-radius diagram of MM5 forecast rainrate (mm h^{-1}) in Rita from 1200 UTC 20 September – 1200 UTC 23 September using 1.67 km (left) and 5 km (right) grid resolution. The model was initialized at 0000 UTC 20 September using the NOGAPS forecast fields as lateral boundary condition. The 1.67 km forecast had an eyewall replacement cycle as observed in the actual event, whereas 5 km forecast did not.

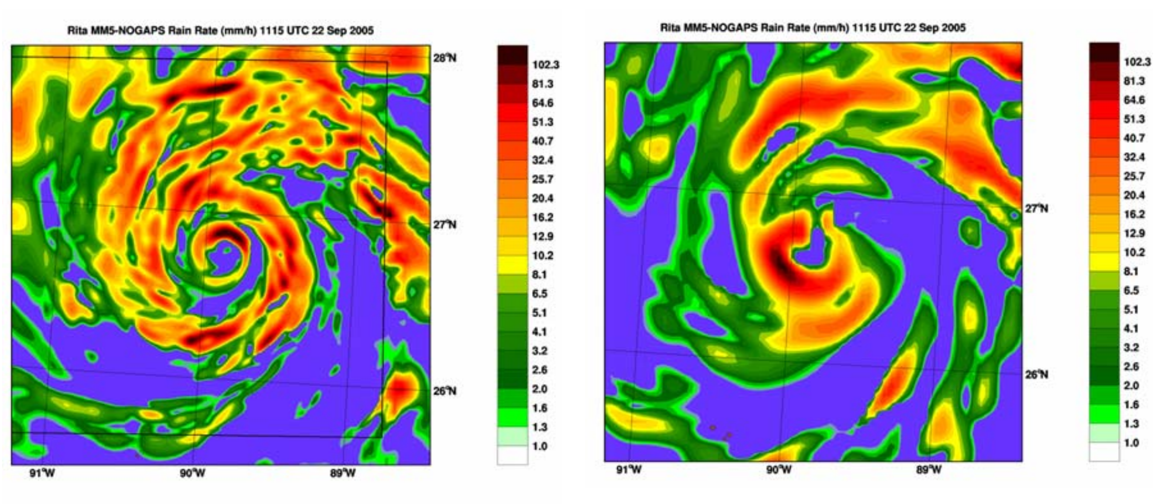

Figure 4.4b. MM5 forecasted rainrate (mm h^{-1}) in Rita at 1115 UTC 22 September using 1.67-km (left) and 5-km (right) grid resolution. The model was initialized at 0000 UTC 20 September using the NOGAPS forecast fields as lateral boundary condition. The 1.67-km forecast shows a primary and secondary eyewalls as observed, whereas 5-km does not.

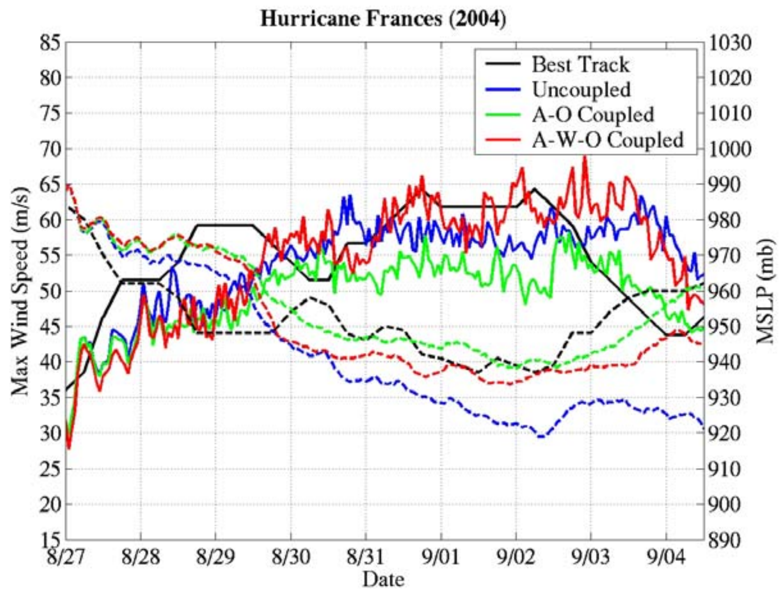

Figure 4.5. Observed (the NHC best track in black) and simulated MSLP (dashed lines) and maximum wind speed (solid lines) from the fully coupled atmosphere-wave-ocean model (red), coupled atmosphere-ocean model (green), and uncoupled atmosphere model (blue), for Hurricane Frances (Chen et al. 2006).

Chen also presented evidence to the HIRWG of the necessity to properly couple the simulated storm system to the underlying ocean. For example, Chen's simulation of Hurricane Frances (2004) in Figure 4.5 was done using the coupled atmosphere-wave-ocean model with the wind-wave coupling parameterization developed in CBLAST (Chen et al. 2006). The coupling to the ocean circulation model improves the storm intensity by including the storm-induced cooling in the upper ocean and SST, whereas the uncoupled atmosphere model with a constant SST over-intensifies the storms. However, without coupling to the surface waves explicitly, the model underestimates the surface wind speed, even though the minimum sea-level pressures are close to the observed values. The full coupling with the CBLAST wind-wave parameterization clearly improves the model simulated wind-pressure relationship that is a key issue in hurricane intensity forecasting.

NOTE: NCAR has also conducted subsequent simulations that confirm many of Chen's result.

The HIRWG finds that 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 forecast skill for both intensity and the overall wind and precipitation structure of hurricanes. All evidence presented to the HIRWG indicates that these are critical elements needed in operational forecast models. 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 high resolution.

Recommendation 3: (Short-term) Support should be provided for development and validation of high-resolution, coupled hurricane-ocean models that incorporate appropriate atmospheric and oceanic physics representations derived from the results of recent field experiments, such as CBLAST and RAINEX.

Recommendation 4: (Medium-term) NOAA should reprioritize existing or acquire the necessary computing system capability to produce approximately 1-km-resolution hurricane forecasts.

Recommendation 5: NOAA should plan additional field experiments aimed at validating and improving high-resolution coupled models.

5 Novel Methods for Data Assimilation

Because of the need for nested grids to achieve sufficient resolution for intensity forecasting, numerical simulation of hurricanes presents a complex mix of both initial and boundary value problems. Therefore, providing accurate initial conditions for numerical models is a critical component for better forecasts of hurricane intensity. 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 versus retrieved products, observation errors, background errors, data quality control, etc.

Data assimilation techniques may be subdivided into time-dependent and static modes:

- Static modes include 3DVar, which may include a cycling component, and optimal interpolation;
- Time-dependent modes include 4DVar, nudging, and EnKF.

Data assimilation is still an open research field and there is no definitive evidence of which approach is best for hurricane 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 hurricanes.

Recommendation 6: (Medium-term) A 4D data assimilation system for hurricane forecasting should be developed as a priority. This development should explore the advantages and disadvantages of both 4DVar and Ensemble Kalman Filter approaches to assimilating the diverse range of data that are available.

Recommendation 7: 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.

Since hurricanes 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, that must be handled in a logical manner using data assimilation techniques. Current forecast systems (GFDL) do not assimilate such data. While the HWRF version 1 will have this capability there is still a major disconnect between the available data and the assimilation of these data into the hurricane forecast models. For example, aircraft, satellite and radar data (both Doppler winds and reflectivity) are not included, 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 limited 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 8: (Short-term) Airborne and surface-based radars offer the best opportunity to observe mesoscale fields in the inner core region but full realization of their potential requires real time assimilation into models. A focused program aimed at assimilating radar data into HWRF is recommended, with the goal of operational testing in 2007.

6 Improved Observations of the Hurricane and its Environment

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

It was not possible for the HIRWG to make a comprehensive survey or assessment of the current observing systems. Rather, the HIRWG concentrated on identifying gaps and concerns, both with the actual observations and the manner in which they are incorporated into the forecast process. In addition, the HIRWG attempted to identify opportunities for enhancements to current systems and new systems that would make them more effective in supporting the mesoscale modeling effort.

6.1 Observing System Experiments (OSEs) and 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 has been developed in the optimal strategies of deploying mobile observing systems, and NOAA should ensure that this expertise is retained and enhanced. Our observing systems should evolve to encompass new instruments and in response to these new datasets, new knowledge and forecast techniques.

Observing System Experiments (OSE) and Observing System Simulation Experiments (OSSEs) are powerful and relatively inexpensive ways 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[3]. Any new or

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[3] **Observing System Experiments** (OSE) allows for the objective assessment and comparison of existing operational observing systems in a controlled software environment. Observations that represent the characteristics of the observing system being tested are synthesized from forecasts generated by a sophisticated numerical prediction model that is independent of the operational assimilation system being used. These forecasts are referred to as the "true", or "nature" atmosphere. The forecast model used to produce the "nature" atmosphere must have a known performance history, and must be calibrated against reality. The observations that are synthesized from the "nature" atmosphere must mimic, as close as possible, those observations from the real observing system that is being assessed. … The software system described above can be extended to include proposed, next-generation, observing systems. These assessments are performed as **Observing System Simulation Experiments (OSSEs)**. Observations for these experiments are simulated using projected instrument characteristics. In this context future-observing systems can be compared to existing systems to determine if there is value added in the form of improved forecast skill.

Adapted from ***http://cimss.ssec.wisc.edu/model/osse/osse.html*** 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 fine tuning the observing system to the forecast needs.

Recommendation 9: Observing System Simulation Experiments (OSSEs) should be undertaken to determine the optimal configurations of observing systems for improved forecasts and as a guide to realigning and improving the current observing systems.

6.2 Satellite Observations

Current satellite systems combine dense spatial information with periodic revisit, but with relatively poor vertical resolution. These data are critical for monitoring hurricanes over the ocean, and provide both detailed observations and the larger-scale context for targeted aircraft and related observing systems. Moreover, these data are also important to improve reanalysis data and initial conditions for hurricane forecasting through data assimilation. The use of satellite data to estimate hurricane intensity (e.g., the 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.

There are two different types of satellites: polar-orbiting and geostationary. Polar-orbiting satellites (NPOESS) observe the hurricane at low altitudes for brief intervals twice per day and they may miss important information. Therefore, the synthesis of different satellite data (e.g., QuikSCAT, Special Sensor Microwave Imager (SSM/I), the Tropical Rainfall Measuring Mission (TRMM), and European Space Agency ERS-2) is important. Geostationary satellites provide continuous coverage (every few minutes in some cases), but their high altitude impedes attaining desired resolution. A summary of current satellites of importance to hurricane forecasting is provided in Appendix 6.

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. While TRMM can observe hurricanes for only brief periods twice a day, these observations have been lauded by forecasters 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 life expectancy and a replacement is many years away. Another example is the radar altimeter such as the one found on the TOPEX Poseidon satellite. In recent years, these altimeters have proven key for assessing the critical ocean heat content, thus providing insight on the impact of ocean processes on rapid intensity changes. Other examples of NASA satellites that have potential for hurricane-related observations are the MODIS instruments on the AQUA and TERRA satellites.

A major adjustment in the NPOESS program has been announced in June 2006. In addition to a reduction from a planned series of six satellites to only four, the schedule has been delayed, and some instruments have been cancelled. Of particular concern to the HIRWG is the resultant decreased microwave coverage, because this instrument provides estimates of intensity, rainband structure, degree of hurricane organization under cirrus decks, and quantitative estimates of the rain rates. Also of concern is the potential gap in radar altimetry coverage that will result from removal of this instrument.

Recommendation 10: (Medium-term) The strengths and weaknesses of current and past satellite observations for hurricane forecasting should be fully evaluated using OSEs, with direct involvement from that portion of the academic community focused on operational products, and with the aim of developing a comprehensive plan in support of current initiatives and to recommend future directions.

6.3 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 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 A7.3.

The HIRWG endorses the installation of radar on the Gulfstream-IV (G-IV), which will provide a substantially expanded capacity for this aircraft to provide detailed information on hurricane core and rainband structure. However, it is emphasized that full benefit from this important system will not be achieved unless it is accompanied by implementation of a data-assimilation system capable of ingesting these data into forecast models, as discussed in Section 5.3. The HIRWG also viewed with concern information that the deployment of the Stepped Frequency Microwave Radiometer (SFMR) on the US Air Force C-130s may be delayed. This instrument provides valuable surface observations in the region of strongest wind speeds, and its rapid implementation is encouraged.

Recommendation 11: The planned G-IV radar implementation is endorsed, as is the SFMR deployment on USAF C130s

6.4 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 humans 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 A7.4. However, there is a wide variety of UAS flying and in various stages of development. The endurance of UAVs extends out to months with flight altitudes ranging from the surface to 100,000 ft. Each type has advantages and disadvantages. All UAS 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 the region close to the surface where damaging winds and important energy exchanges occur.

The HIRWG notes that a successful trial reconnaissance into Ophelia was made using the Aerosonde UAS in a joint NOAA/NASA program. This demonstration showed potential to provide near-surface observations that can be critical to intensity forecasting, and which are currently poorly sampled by other observing systems. However, further trials are needed to gain operational experience with such systems and to ascertain if LALE aircraft can routinely provide such data. The HIRWG endorses such trials as a logical next step.

In addition to in situ measurements from the aircraft, HIRWG notes that many innovative approaches for the use of UAS, such as the dropping of long-loitering microprobes directly into the eye, have been proposed, with some demonstration systems in development. However, the HIRWG was not able to undertake sufficient investigation to examine comprehensively the relative benefits of UAS vs. manned aircraft and other observing systems.

Recommendation 12: NOAA should establish an independent committee to examine the potential role of UAS for hurricane observations. This examination should include use of OSSEs to assist objective determination of the potential impact of these observations.

Recommendation 13: 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.

6.5 Surface Observing Systems

The HIRWG was presented with no evidence of major deficiencies in the current deployments of surface observing systems (e.g., ASOS). Indications are that the current level of deployment is sufficient for present purposes and should be maintained.

A need was identified for improved survivability of wind instruments during hurricane landfall, particularly for very intense winds with airborne debris. The supporting power and telecommunications systems need to be hardened as well to ensure survivability. Further, the use of the oil platforms in the Gulf of Mexico should be pursued to provide additional surface observing sites, including locating ground sites for GPS soundings, in support of both research and operations.

6.6 Ocean Observing Systems

In addition to the sea-surface temperature, the upper ocean thermal structure is an important requirement for calculating the ocean-air heat and moisture fluxes and ocean heat content that sustain the hurricane. The thermal structure of the ocean is changed by mixing and advection, so observations of ocean currents are also required. For high-resolution, coupled atmosphere-ocean hurricane models, the initial ocean thermal structure and current conditions must be specified on horizontal scales comparable to the grid scale in the model. Few *in-situ* ocean observations such as bathythermographs or fixed buoys exist. Space-based radar altimeters have been used to estimate the pre-storm, spatial distribution of the ocean heat content. Aircraft-deployed expendable bathythermographs, (AXBTs) have been very influential in describing the ocean thermal structure changes in response to hurricanes, but no AXBT observation programs exist for providing the real-time conditions to a numerical model. Although some assimilation of the few available observations is attempted, ocean data assimilation is not as advanced as atmospheric data assimilation. The advantage of the model-based data assimilation approach is that ocean thermal structure and currents are available at each grid point. The disadvantage is that these ocean thermal structure and current inputs are model solutions and are not constrained by in-situ observations.

Since the HIRWG was presented evidence that the GFDL coupled model has no intensity prediction skill over the ocean, the HIRWG observes that a real-time ocean observation program will be helpful in validating the HWRF and other models for hurricane intensity prediction.

Recommendation 14: (Short-term) NOAA should develop a program for deploying Airborne Expendable Bathythermographs (AXBTs) to define the initial conditions for high-resolution, coupled ocean-hurricane prediction via an appropriate regional ocean data assimilation system that uses the previous model solutions as the background.

In addition to AXBTs, there is a critical need for other ocean surface and subsurface observations. These include observations of velocity, shear, salinity, and pressure using a combination of Lagrangian floats and drifters. Wave field parameters, such as observations of breaking waves, and of sea spray may also be important to understanding the hurricane intensification puzzle. It is critical that a protocol to assimilate these data into coupled atmosphere-ocean models is developed as well.

Recommendation 15: To conduct OSSEs to determine optimal ocean observing systems in the Gulf of Mexico and in the western Atlantic, noting that these may be different.

6.7 Land-Based Radar

Land-based WSR-88D radars currently provide essential monitoring of hurricanes in the hours prior to landfall. The HIRWG was presented with no major issues associated with the current network as used in this monitoring mode. However, as recent events have shown, an urgent need exists for robust communications and emergency power systems that are able to withstand high wind conditions.

As an outgrowth of its assessment of current observing systems and opportunities for enhancement, the HIRWG observed that the land-based radars are an underutilized resource. Assimilation of high-resolution radar data has been shown to provide mesoscale models with valuable information not available from any other source. It is highly desirable for modeling purposes that *all* available radar data – aircraft (P3, G-IV) and land based (WSR-88D; TDWR and other FAA radars; mobile radars and TV station radars where available) -- be collected and assimilated to provide a composite radar picture of a hurricane and its environment. Such a composite would complement and supplement satellite measurements as an input to numerical models. It would be of value everywhere along the coastal zone, but particularly along the Gulf coast, where in some situations multiple radars can observe a storm from different angles.

Given the potential importance of radar data to modeling efforts, it is desirable to assess the configuration of each coastal radar to determine if changes might be made to optimize the ability of each radar to observe hurricanes. In particular, it may be desirable to raise the height of the antenna to maximize the distance to the radar horizon. While the HIRWG did not have the time to explore novel radar configurations, it notes for future consideration that radars on oil platforms and aloft in aerostats might offer opportunities for observing storms well out to sea.

Recommendation 16: To assimilate all available radar data, including aircraft (P3, G-IV) and land based (WSR-88D; TDWR and other FAA radars; TV station radars) and use this as an input to the mesoscale modeling system. Further, to conduct OSSEs to determine optimal configurations for land-based radar systems, especially around the Gulf of Mexico, in support of the mesoscale modeling effort.

6.8 Balloons and Rawinsondes

The HIRWG received suggestions for novel approaches using balloons and rawinsondes, including automated launching systems on islands, and the use of mylar constant-pressure balloons in swarms to provide observations within the hurricane circulation. The HIRWG recommends that these approaches be considered as part of the longer-term assessment of all observing systems, together with OSSEs to ascertain their potential impact on forecast skill.

7 Focused Applied Research and Development

The NHC Director has identified rapid intensity changes as one of NHC's major forecast issues. Rapid intensification represents the dreaded "forecaster's nightmare" scenario and can lead to over prediction of landfall intensity to accommodate the "worst case" scenario. As indicated in Section 3.2, 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 physics and interactions of importance to the intensity problem. These have been identified (Section 4.2) as including the interaction of the hurricane with its environment, inner-core dynamics and microphysical processes, rainband dynamics, ocean processes and oceanic-atmospheric interactions. This section discusses some key research activities and needs, together with areas of high potential for an operational return.

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 dropwindsonde and 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.

Another contributor to rapid intensity changes is the development of a secondary eye wall, with subsequent weakening as the primary eye wall decays and then rapid intensification as the new, secondary one contracts inwards. This phenomenon often occurs in category 4 and 5 hurricanes and is complicated further by their tendency to also develop eye-wall vortices. Evidence presented to the HIRWG leads us to conclude that the HWRF version 1 will have insufficient resolution and cloud physics to be able to predict these events. While a capacity to resolve the fine-scale structure of the maximum wind region is essential, there remain considerable uncertainties on the relative roles of inner-core dynamics, microphysical processes, ocean processes, oceanic-atmospheric interface processes and environmental forcing on initiating this critical phenomenon.

It is also well established that the ocean heat content plays a critical role in determining hurricane intensity. However, the processes that support, and inhibit, exchange of this energy at the ocean surface remain problematic. For example, the effects of sea spray on the heat, moisture, and momentum fluxes in the high-wind conditions of a hurricane are not well understood. The report of the Air-Sea Interaction workshop sponsored by NCEP in 2005 lists eight ocean data sets that could be used to validate the ocean model physical process representations occurring under hurricanes. A recent major experiment (CBLAST, Black et al. 2006), has gathered an unprecedented high-resolution data set for quantifying such energy exchanges. Because of the turbulent nature of the surface environment, the observational and computational challenges are considerable and improved understanding and forecast capacity requires a combination of dedicated observational campaigns, analytical methods, and high-resolution idealized and real-case numerical simulations. Research is also required on the optimal way of coupling the ocean and atmosphere for operational models. Observational studies in the Gulf of Mexico and the Gulf Stream are required to validate coupled models of varying complexity and physical processes.

Rainbands are another ubiquitous feature of hurricanes. They dominate the asymmetric structure of the hurricane circulation outside the primary eyewall and are often associated with many changes occurring in the hurricane core. While the asymmetries they introduce are widely believed to be associated with reduction of intensification potential, they may also contribute to intensification in some circumstances. Clearly, further applied research is needed to more fully understand the nature and role of the rainbands in the evolution of a hurricane. A recent major field program, RAINEX (Houze et al. 2006), collected an unprecedented volume of data providing detail on a number of rainbands in Hurricanes Katrina and Rita. The HIRWG sees great potential for improved understanding and prediction of both the rainbands and their impact on the overall hurricane structure and intensity.

Regardless of whether these critical hurricane intensity and structure change events are forced by internal dynamics, microphysics, or responses to other atmospheric or oceanic changes, these intensification events involve modifications in the core of the hurricane. Research is required that identifies observationally accessible, reliable precursors of rapid intensification/weakening and eyewall-replacement cycling.

Recommendation 17: (Short- to medium-term) Priority should be given to enhanced support for research to advance understanding of phenomena related to predictability of rapid intensification and secondary eyewall phenomena. This should include investigations of core processes such as heat and momentum exchanges with the surface and across the eyewall and the impact of atmospheric and oceanic interactions.

The HIRWG finds that significant improvements to hurricane-track prediction are being made by application of poor-man ensemble (consensus)-forecasting procedures. Accordingly, the development of a systematic procedure for the preparation of real time ensemble forecasts of hurricane intensity could yield a significant upgrade in predictive accuracy. The following are select questions that remain to be answered:

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

8 Attaining Critical Mass

The HIRWG has been presented evidence that new research models from several institutions will contribute to future improvements for hurricane intensity forecasting. These models can be used to try out new ideas, develop new physics packages, and assist in improving understanding of hurricane structure. 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 19: (Short- to medium-term)The hurricane modeling capability at HRD should be increased, and improved and coordinated interaction between NCEP, HRD, NCAR, and the broader community established, with the immediate goal of substantially enhanced exchanges of ideas, requirements, and support. This should be a two-way effort with operations giving serious consideration to research developments and research noting operational needs in setting their research priorities.

9 Accelerate Transfer from Research to Operations

The NOAA Strategic Plan proposed the formation of testbed centers to facilitate the transfer 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 generating operational products for the National Hurricane Center and hurricane modeling innovations at the NCEP/EMC, either for the operational GFDL hurricane model or the HWRF model to be implemented in 2007. Approximately 75 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 some success in forecasting hurricane intensity changes, and indicate that much higher horizontal resolution and more complex representation of physical processes are required.

Unfortunately, funding for JHT has decreased even in view of its success. In addition, the JHT is not a proper mechanism for testing completely new hurricane intensity models 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 these tasks. The Developmental Testbed Center (DTC) at NCAR has the requisite capabilities for such testing.

Recommendation 20: The Developmental Testbed Center and Joint Hurricane Testbed should be tasked with improving links between NOAA operational efforts and the wider research community. These links should include evaluations of and intercomparisons between NOAA models and community models, together with the establishment of enhanced visitor and post-doctoral programs.

Recommendation 21: JHT funding should be restored to previous levels, or to higher levels if a significant number of well-qualified proposals continue to be declined for lack of funds for these critical projects.

Recommendation 22: (Short-term) The Developmental Testbed Center (DTC) needs to be fully implemented and adequately funded for the task of testing new research models that have demonstrated potential for skillful hurricane intensity forecasts. This must include the capacity to test and transfer multi-faceted model applications to operational hurricane forecasting.

10 Additional Items from Our Discovery Process

10.1 Communicating the Hurricane Risk and Impacts

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 preparedness actions to be taken. Such actions include securing buildings and property, evacuating the threatened area to protect life, implementing business continuity plans, and preparing for post-landfall response. The time scales for such responses vary from as long as 120 hours for the military and some industries, to 48-72 hours for local evacuations. The track forecast is most important at the longer time scales, and intensity becomes important within 48 hours (Hurricane watches are issued for landfall within the next 36 hours, and hurricane warnings are issued for landfall within the next 24 hours.). A major concern that has been communicated by a number of groups is the danger of a rapid intensity change just before landfall, when actions can no longer be taken.

There is a considerable difference between *forecasting, warning* and *action*:

- Forecasting is the real-time projection of the relevant meteorological and oceanic parameters and is an applied-science problem that 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 that requires understanding of difficult-to-define parameters such as vulnerability and risk, and assessment of the impacts of uncertainties in the forecast process, and the communication of forecasts to a population at risk;
- Action is a complex mix of social science, decision science, behavioral science, natural science and engineering science. Action involves an understanding of the ability of a community to prepare for a storm, the adequacy of the infrastructure to withstand the hurricane, the capacity of a community to respond, and its resiliency to maintain effective communication and logistical infrastructure.

Thus, appropriate community actions before, during, and after hurricane landfall requires both effective research and development aimed at improving intensity forecasting, and a complementary, multidisciplinary combination of scientific, engineering and social considerations. The improvements to the science recommended in this report should be responsive to social and engineering needs and the social and engineering approaches should take adequate account of the inherent limitations of the scientific components of the hurricane intensity forecast problem.

A major consideration for such research and development should be how to effectively communicate the inherent uncertainties in hurricane track and intensity forecasts. 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 23: Research and development aimed at improving hurricane-intensity forecasting should adopt a multidisciplinary approach that includes scientific, engineering and social considerations.

The impact of a hurricane involves more than just the prediction of the maximum wind speed. 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 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. 10.1). These results are indicative rather than prescriptive, but they point toward priorities for further research. These results also indicate the importance of both vortex dynamics and environmental interactions, both of which can only be obtained by very high-resolution modeling.

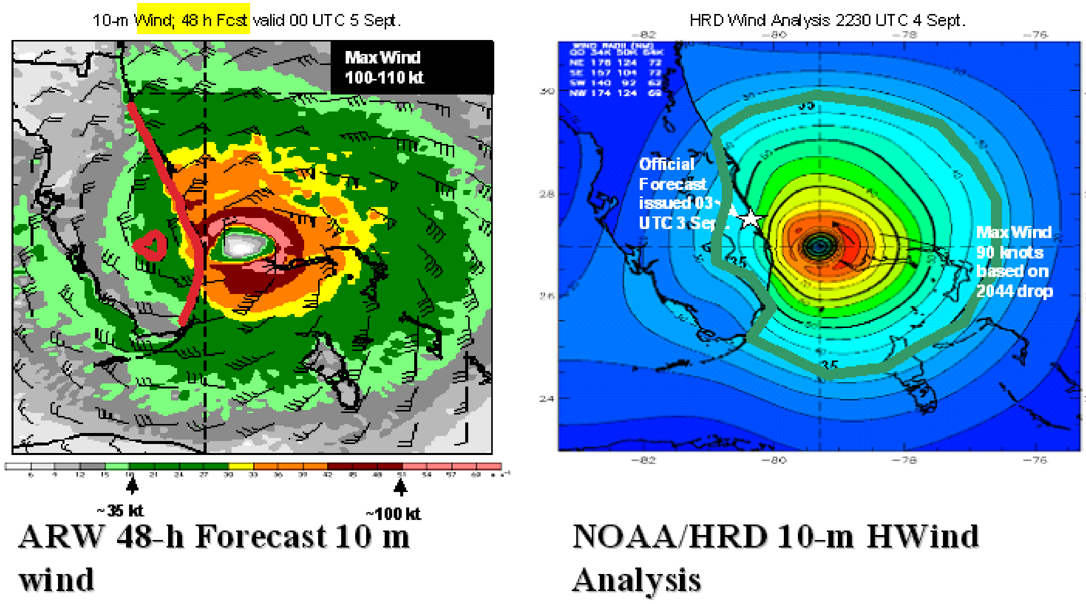

Figure 10.1. Indication of the potential for prediction of wind structure details using the 4 km NCAR WRF: left panel the 48-h forecasts of surface winds, right the HRD Wind Analysis for the same time. The green line on the right panel corresponds to the edge of the 35 kt winds (green area) on the left panel.

An exciting new development has been the coupling of numerical forecasts of high-resolution surface winds and rainfall to GIS-based infrastructure and societal impact models. Such models use a GIS-based view of vulnerable infrastructure together with damage assessment modules to directly forecast the impact of hurricane wind, surge and rain on a community. Products from such models have the potential to provide direct advice to emergency managers of likely disruptions to infrastructure, optimal evacuation routes, and likely recovery times for critical systems (such as power grids, generator stations, and businesses).

A collaborative program between NCAR and Los Alamos National Laboratory has led to real-time testing of a prototype system in 2005, which will be continued in 2006.

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

10.2 Potential Contributions from Reduced Models and Statistical Techniques

While the HIRWG has strongly recommended a major emphasis on high-resolution numerical modeling to improve hurricane intensity forecasting, continued development of reduced models and statistical approaches is also prudent. 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 more quickly than sophisticated numerical models. The disadvantage lies in the limited subset of information that can be obtained compared to comprehensive numerical models. An example of a reduced dynamical model is the Coupled Hurricane Intensity Prediction System (CHIPS) model (Emanuel et al., 2004). An example of a statistical technique is the Statistical Hurricane Intensity Prediction System (SHIPS) (DeMaria et al. 2005).

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

10.3 Verifying Hurricane Structure Forecasts

Nearly fifty years of hurricane research and reconnaissance data have been collected by HRD, USAF, NASA, and others. These data represent a valuable national resource for research and for verification of new forecasting techniques.

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

The increasing capacity of numerical models to forecast not only the maximum wind speed, but details of the wind field and precipitation distribution of the hurricane, combined with the expected move toward more direct impact forecasting, requires a reconsideration of the way in which validation and verification are accomplished. The HIWRG finds that new verification techniques are required to accommodate the increasingly complex societal requirements of the forecast system.

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

10.4 Limitations of Saffir-Simpson Scale

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) that the major difference that attends a change in category 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 speed).

However, the HIRWG finds that 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 eliminated from the scale and handled separately. Further, the HIRWG finds 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. Information on the uncertainty in the forecast can also be important to some decision makers.

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

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

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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: Hurricane Intensity Research Working Group Timeline

Winter and Spring 2005	NOAA Science Advisory Board Meeting - date unknown -- discussed the need for this type of a working group.
Summer 2005	John Snow and members were formed under the council of Mike Uhart, SAB Executive Director
1-2 September 2005	First meeting was called in Silver Spring, Maryland
21 September 2005	Conference call - coordinate a meeting National Centers for Environmental Prediction (NCEP), Camp Spring, MD
6-7 October 2005	A subset of HIRWG members were given an NCEP briefing and time to discuss topics with individuals
19 October 2005	Conference calls – coordinates findings a NCEP and plan an upcoming meeting in Miami
17-18 November 2005	(Postponed 10/27/05) Second HIRWG Meeting
10 November - 15 December 2005	A series of conference calls were held to keep the team on track until the second meeting could occur in January
10-11 January 2006	Second HIRWG meeting occurs in Miami, Florida – Also in attendance at this meeting were Dr. Michael Crosby, NSB Executive Director, representing the National Academy of Science Hurricane study team
30 January – February 2006	American Meteorological Society and other meetings – several working group members coordinated and attended proceedings pertinent to the HIRWG mission National Hurricane Conference - subset Interdepartmental Hurricane Conference – subset AMS Meeting in Monterey California – subset
1-2 March 2006	Third HIRWG meeting was held at Table Mesa, Boulder, Colorado

April – May 2006	A series of conference calls were held to coordinate writing efforts and discuss issues with key hurricane and related experts (Ants Leetma and research staff at GFDL; Kerry Emanuel at MIT)
24 May 2006	The preliminary HIRWG report was posted as a Federal Register Notice
13-14 June 2006	Fourth HIRWG meeting was held, Norman, Oklahoma
26 June 2006	Final comments from the FRN are made available
30 June 2006	Minority report – submitted to Snow for inclusion as Appendix 1 to near-final report
5 July 2006	Near-final HIRWG Report submitted to SAB staff
25 July 2006	Majority report accepted by the SAB; minority report directed to go public comment via the Federal Register process
Mid-August 2006	Minority report posted for public comment via Federal Register process
Mid-September 2006	Comment from the public sent to minority report authors
Late September 2006	Minority report authors elect not to respond to comments received; they request their report be submitted as a standalone report
6 October 2006	Minor report sent to new SAB chair, David Fluharty
8 October 2006	Lightly edit/revised majority report sent to new SAB chair, David Fluharty, for forwarding to Admiral Lautenbacher

Appendix 4: Meeting Agendas

This appendix provides agendas of the three meetings at which the Working Group heard from individuals involved in hurricane forecasting and research:

Silver Spring, Maryland – 1-2 September 2005

Miami, Florida - 10/11 January 2006

Boulder, Colorado – 1-3 March 2006

The HIRWG held a fourth meeting in Norman, Oklahoma on 13-14 June 2006 which was devoted to preparation of the WG's report.

NOAA Science Advisory Board
Hurricane Intensity Research Review Working Group (HIRWG)

Meeting 1-2 September 2005

Agenda

Thursday, 1 September

8:30 - 9:00 AM	Welcome and introductions (SAB)
9:00 - 9:15 AM	NOAA perspective on HIRWG - Dr. Jim Mahoney
9:15 - 10:00 AM	HIRWG charge and introduction to agenda - Prof. John Snow
10:00 - 10:15 AM	Break
10:15 - 11:00 AM	Committee introductions – HIRWG committee members
11:00 - 11:15 AM	What is the hurricane intensity forecast problem and what is our current level of skill and understanding? - Max Mayfield (NCEP/TPC) via videoconference
11:15 - 12:00 noon	Operational modeling research addressing hurricane intensity - Dr. Naomi Surgi (NCEP/EMC)
12:00 - 1:00 PM	working lunch (lunch will be provided in the meeting room)
1:00 – 1:30 PM	Hurricane intensity research issues and objectives - Dr. Frank Marks or Dr. Robert Atlas (AOML/HRD)
1:30 - 2:00 PM	NESDIS hurricane intensity research objectives and applications - Dr. Mark DeMaria (ORA/CIRA)
2:00 - 2:30 PM	USWRP research community (NCAR, NASA, NAVY, NSF) activities and research on hurricane intensity– TBD (Dr. Robert Gall or Prof. Russ Elsberry)
2:30- 2:45 PM	Transition of research into operations (USWRP/JHT) – Dr. Jiing Gwo Jiann (NCEP/TPC) via videoconference
2:45 - 3:00 PM	Transition of research into operations (EMC) – Dr. Naomi Surgi (NCEP/EMC)
3:00 – 3:15 PM	Break
3:15 - 3:30 PM	Role of OFCM in hurricane intensity research - Bob Dumont
3:30 - 4:00 PM	Overview of Resources – TBD

4:00 - 4:15 PM	Review of materials available to the Committee - Roger Pierce (OAR)
4:15 – 5:00 PM	Synopsis of key hurricane intensity research issues

Friday, 2 September

8:30 – 9:30 AM	Review and discussion of key hurricane intensity research issues
9:30 - 10:00 AM	Working group discussion of information presented (HIRWG members plus internal committee)
10:00 - 10:15 AM	Break
10:15 - 12:00 noon	Working group discussion of information presented (HIRWG members plus internal committee)
12:00 - 1:00 PM	Working Lunch (lunch will be provided in the meeting room)
1:00 - 3:00 PM	Game plan (schedule, site visits, future meetings, information needed) and charge to support staff.

NOAA SAB HIRWG – Miami Meeting 10/11 January 2006

Tentative Agenda

Day 1 – Tuesday, 10 Jan 06

7:00 am	Group breakfast at hotel
7:45 – 8:30 am	Travel to TPC
8:45 am	Welcome, introductory remarks – J. Snow; administrative matters – R. Pierce
	Review the agenda and goals of the meeting – J. Snow
9:00 am*	Presentations by and discussions with Max Mayfield -- Director Chris Landsea (TPC SOO) and/or TPC Lead Forecaster – Roger Pierce checking availability
11:00 am*	Hugh Willoughby – FIU/International Hurricane Research Center – invitation extended by JTS
11:30 am*	Executive Session – what have we heard???
12:00 N-- 1:30 pm	Travel to AOML (lunch en route)
1:45 pm	Reconvene; remarks by and discussion with J. Mahoney and R. Spinrad
2:15 pm*	Presentations by and discussions with Bob Atlas, Dir. AOML
3:00 pm*	Shuyi Chen, Univ Miami/RSMAS – Otis Brown extending invitation
3:45 pm*	Robert Hart, FSU
4:30 pm*	Executive Session – what have we heard?; remarks and comments from Greg Holland and Peter Webster
6:00 pm	Adjourn for the day; return to hotel
7:30 pm	Dinner at hotel

Day 2 – Wednesday, 11 Jan 06

8 am Travel to AOML

8:20 am Reconvene

Review agenda for the day – J. Snow

8:30 am* Strawman outline of the report – overview and rationale – J. Snow

9:00 am* Discussion

Report outline
Boilerplate writing assignments (e.g., statement of the problem)

Identify the Key Issues (review charge – what have we been asked to do?)
Preliminary Recommendations (make writing assignments as discussion proceeds)

12:00 N – 1:00 pm Lunch Break (RSMAS cafeteria)

1:00 pm* Reconvene; discussion continues

Preliminary Recommendations, continued; Time line for producing the report

4:00 pm* Wrap-up
Review
Action items and next steps
Administrative matters

5:00 pm Adjourn; return to the hotel or depart for airport

6:30 pm Dinner for those remaining

* These will essentially be executive sessions with just the Working Group, the NSB liaision(s), and a staff person to serve as a recorder.

NOAA SAB HIRWG – Boulder 1-3 March 2006

NCAR Fleischman Building (Mesa)

Day 1 – Wednesday March 1

7:30 am	Group breakfast at hotel
8:30 am	Arrival and registration
8:45 am	Welcome, introductory remarks – J. Snow; administrative matters – F Marks
	Review the agenda and goals of the meeting – J. Snow
9:00 am with	Research Activities: Presentations (20 min) by and discussions Wayne Schubert: Inner core dynamics Rick Anthes: Impacts of Greenhouse Warming Jeff Lazo: Social and Economic Aspects Mark DeMaria: Satellite-based intensity analysis (15 min, moved here so the CSU folks can come down together)
11:30 am*	Executive Session – what have we heard?
12:30-- 1:30 pm	Lunch in cafeteria
1:30 pm with	Modeling Activities: Presentations (20 min) by and discussions Greg Holland: Overview Bob Gall: The Joint Numerical Test bed Chris Davis: High resolution modeling impact on intensity forecasting Chris Snyder and Dusanka Zupanski: Data assimilation Brian Bush: Forecasting impacts
4:00-6:00 pm*	Executive Session – what have we heard?
6:00 pm	Adjourn for the day; return to hotel
7:30 pm	Dinner at the Red Lion Inn

Day 2 – Thursday March 2

8:20 am	Reconvene
	Review agenda for the day – J. Snow
8:30 am	Observing Systems: Presentations by and discussions with Roger Pielke Jr: Coastal Demography and Growing Impacts Louie Grasso: Next generation GOES (15 min) Sara Summers: High-Altitude UAVs (15 min) Greg Holland: Low-altitude UAVs (15 min)
10:00 am*	Executive Session – what have we heard?
12:00– 1:00 pm	Lunch Break (cafeteria)
1:00 pm*	Reconvene; Finalization of Preliminary Report Chapters 1-3 with 30 minutes for each
4:00 pm*	Continue report discussions Chapters 4-6 with 30 minutes for each
5:30 pm	Adjourn; return to the hotel
6:30 pm	Dinner

Day 3 – Friday March 3

8:20 am	Reconvene
	Review agenda for the day – J. Snow
8:30 am*	Individual writing assignments aimed at completion of report
11:00 am*	Executive Session: Finalizing Preliminary Report
12:30– 1:30 pm	Lunch Break (cafeteria)
1:00 pm*	Reconvene in executive session: Finalization of Report and schedule for completion of committee activities
3:00 pm	Finish

* These will essentially be executive sessions with just the Working Group, the NSB liaison(s), and a staff person to serve as a recorder.

Appendix 5: Acronyms

3DVar	Three-dimensional Variational Data Assimilation
4DVar	Four-dimensional Variational Data Assimilation
AOML	Atlantic Oceanographic and Meteorological Laboratory
ARW	Advanced Research WRF Model
AXBT	Airborne eXpendable BathyThermograph
CAMEX	Convection and Mesoscale Experiments
CBLAST	Coupled Boundary Layer Air-Sea Transfer
CHIPS	Coupled Hurricane Intensity Prediction System
CPU	Central Processing Unit
DTC	Development Testbed Center
EMC	Environmental Modeling Center
EnKF	Ensemble Kalman Filter
ERS	European Remote-Sensing Satellite
GIS	Geographic Information System
G-IV	Gulfstream IV
GDAS	Global Data Assimilation System
GFDL	Geophysical Fluid Dynamics Laboratory
GFDN	Navy version of GFDL
GFS	Global Forecast System
GPS	Global Positioning System
HALE	High-Altitude, Long-Endurance
HIRWG	Hurricane Intensity Research Working Group
HRD	Hurricane Research Division
HWRF	Hurricane Weather Research and Forecast
JHT	Joint Hurricane Testbed
LALE	Low-Altitude, Long-Endurance
MM5	Fifth-Generation NCAR / Penn State Mesoscale Model version 3
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NCEP	National Centers for Environmental Prediction
NHC	National Hurricane Center
NMM	Nonhydrostatic Mesoscale Model
NOAA	National Oceanic and Atmospheric Administration
NPOESS	National Polar-orbiting Operational Environmental Satellite System
NRL	Naval Research Laboratory
NSF	National Science Foundation
NWS	National Weather Service
OAR	Oceanic and Atmospheric Research
ONR	Office of Naval Research
OSE	Observing System Experiments
OSSEs	Observing System Simulation Experiments
PBL	Planetary Boundary Layer
PDT	Prospectus Development Team

POM	Princeton Ocean Model
RAINEX	RAINband Experiment
R&D	Research and Development
SAB	Science Advisory Board
SFMR	Stepped Frequency Microwave Radiometer
SHIFOR	Statistical Hurricane Intensity Forecast
SHIPS	Statistical Hurricane Intensity Prediction System
SSM/I	Special Sensor Microwave Imager
TOPEX	TOPography Experiment
TRMM	Tropical Rainfall Measuring Mission
UAS	Unmanned Aerial Systems
UAV	Unmanned Aerial Vehicle
USAF	U.S. Air Force
USWRP	U.S. Weather Research Program
WRF	Weather and Research Forecast

Appendix 6: Observing Systems

7.1 Satellites

A summary of current satellites of importance to hurricane forecasting is provided in Table A7.1, 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, SSM/I, and 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.

Table A7.1: Summary of current satellite systems relevant to hurricanes

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	40 pressure levels from 0.1 to 1000 hPa	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	
Cosmic	PO	Phase delay or bending angle	300 km	100 m	Nil
GOES	GS	Hurricane position and intensity, cloud tracking winds	n/a	n/a	Height estimation of winds

Several new satellite systems are scheduled for operation within the next five 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.

Table A7.2: Summary of planned satellite systems relevant to hurricanes

Satellite Instrument	Type	Observations	Resolution		Deficiencies
			Horiz.	Vert.	
ASCAT	PO	Sea surface wind vectors			
ATMS	PO	Sounding temperature Precipitation	33 km	??	
GOES-R	GS	Higher spatial and temporal resolution than GOES data			

7.2 Manned Aerial Systems

Table A7.3: Current manned aircraft with demonstrated capability for research and operations reconnaissance of tropical cyclones.

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

Aircraft	Speed/Endurance/ Range	Altitude	Instruments	Mission
NASA ER-2	400 kt, 9 h, 3600 nm	60,000 ft	instrument payload driven by proposals – some available in CAMEX and TCSP missions include: 1-Hz flight-level data (inertial and GPS navigation), GPS dropwindsonde, SATCOM, EDOP vertically profiling Doppler radar, numerous passive remote sensors	Research
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

7.3 Unmanned Aerial Systems

Table A7.4: Specifications for the Global Hawk and Aerosonde UAS.

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 packages, flown extensively) Dropsonde and radar proposed	Research and Operations, Environmental 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