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To: NOAA Science Advisory Board
Sent electronically to: noaa.sab.comments2@noaa.gov
From: Roger Lukas, Professor of Oceanography, University of Hawaii
Date: June 21, 2006
Re: NOAA SAB Hurricane Intensity Research Working Group (HIRWG) Preliminary Report

In response to the draft NOAA SAB Hurricane Intensity Research Working Group Preliminary Report and the Federal Registry notice providing the opportunity for public comment by June 23, 2006, I would like to make the following comments:

1) After careful review of the NOAA HIRWG Preliminary Report, I am of the opinion that the report is very well organized, and clearly written. It contains many important, even critical, recommendations that NOAA will be well served if implemented. Particularly relevant are the recommendations that the wider research community be involved in NOAA's applied research programs for hurricane intensity forecast improvement. There are, however, several important ways that the final report could be improved.

2) The recommendations regarding the need to increase horizontal resolution are very clear, well founded, and compelling. Mention was made of vertical resolution enhancement, but this was not developed in any clear way. That discussion would bring in the substantial boundary layer parameterization problems that we face. In this regard, on page 15 CBLAST and RAINEX are mentioned as "...a possible basis for both improved understanding and testing future forecast techniques." CBLAST and RAINEX did result in some excellent case studies. However, reliable sub-grid parameterizations cannot be produced based on a small number of case studies only, and these programs did not measure all variables needed for improved boundary layer parameterization. For this purpose, and for testing future forecast techniques, reliable statistics have to be derived from many cases that include observations of all relevant variables.

3) Atmospheric observations were thoroughly discussed. However, there was little discussion of ocean observations. In particular, the utility of satellite altimeters was overlooked in mapping the evolving upper ocean heat content in regions subject to hurricane activity.

4) The preliminary report would have benefited from the inclusion of an oceanographer or two in the Working Group, and certainly someone like Chris Fairall for the air-sea interaction

observation and modeling aspects. Coupling of the atmosphere and ocean was mentioned in a couple of sentences in the report as being possibly important to improved intensity forecasts. Papers referenced in the accompanying HIFI prospectus provide evidence that coupling improvements in hurricane prediction models are as likely to lead to improvements as improved representation of atmospheric physics.

5) Some members of the research community are convinced that ocean physics, and details of air-sea interaction, are critical to forecasting some hurricane intensity changes. The draft preliminary report does not capture this exciting line of research. Indeed, the interest of oceanographers and air-sea interaction specialists in the HIFI-SSC seems to build on the momentum from results of observations and model experimentation in the past several years.

6) There is a very strong emphasis on Observing System Simulation Experiments in the draft report. Such OSSEs can be helpful in shaping an observing system when models are mature. Given that the current models do not do a good job of intensity prediction, it seems premature to depend heavily on them for guidance in trying to "optimize" hurricane observations that are targeting intensity prediction improvement.

These comments, and other suggestions that are contained within the following Hurricane Intensity Forecast Improvement (HIFI) program prospectus, will hopefully be considered by the NOAA SAB and the HIRWG in any further development of the draft report.

R. Lukas comments

Prospectus
for a
Hurricane Intensity Forecasting Improvement Program

June 21, 2006

HIFI Science Steering Committee

Eric Chassignet (FSU)
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Executive Summary

The devastating 2005 hurricane season in the Gulf of Mexico strongly underscored the fact that, whether for mitigation of risks by evacuation/fortification or for planning relief efforts, accurate prediction of hurricane risks is essential. Such elements of hurricane impact forecasting as prediction of wind damage, wave and storm surge inundation, coastal erosion, and pollutant pathways depend critically on accurate forecasts of hurricane intensity. Unlike the major advances of the past decade in hurricane track forecasting, prediction of hurricane intensity has not significantly improved.

A concerted scientific research effort aimed at improving hurricane intensity prediction is required. This research program should be closely linked with parallel efforts at translating actual forecast improvements into improvements of hurricane impacts prediction and planning. This will require collaborative planning and research by university and government scientists, and it will require cooperative planning and support by federal and state agencies, along with the private sector.

An intensive and sustained program of observations, theoretical analysis and numerical modeling is essential to address the numerous deficiencies in current numerical models used to predict hurricane genesis and evolution. These deficiencies include insufficient resolution of key physical processes, and inadequate parameterizations of processes that cannot be resolved by model grids. A fundamental set of issues surrounds the breakdown, within hurricanes, of long-standing assumptions about the nature of the air-sea interface and the exchanges of heat, moisture and momentum between the atmosphere and ocean.

The research program will require numerous case studies with intensive observations of the structure and evolution of the atmosphere and upper ocean within and around hurricanes. Observations must be made within the most intense part of storms close to the ocean surface. This is a serious challenge, not just because it requires placing sophisticated instruments in the eyes of the storms, but also because it will require placement of observing systems in the path of the storms. Traditionally, adaptive sampling by specially outfitted “hurricane hunter” aircraft is used to make observations, but their ability to observe the conditions near the ocean surface is limited. They must be augmented by autonomous systems that can make critical size and density measurements of spray droplets and bubbles, measurements of turbulence intensity, and standard dynamic and thermodynamic variables.

These observations will provide the basis for improved parameterizations of air-sea interactions within hurricanes, enhanced numerical models, and more skillful predictions of intensity changes. The resulting improvements in intensity forecasts will be of significant value to the coastal states, to the oil industry, and to the reinsurance industry.

Introduction

The devastating 2005 hurricane season in the Gulf of Mexico strongly underscored the fact that, whether for mitigation of risks by evacuation/fortification or for planning and conducting relief efforts, accurate and timely predictions of hurricane risks and impacts are essential. Useful forecasts of hurricane impacts such as prediction of wind damage, wave and storm surge inundation, coastal erosion, and pollutant dispersal pathways depend critically on accurate forecasts of landfalling hurricane intensity including the locations and times that will experience hurricane conditions (Emanuel et al., 2006). Useful public and private sector planning to mitigate hurricane risks depends on numerical hurricane models that properly simulate the statistics of hurricane landfall locations, movements, and strengths. Unlike the major advances of the past decade in hurricane track forecasting, predictions of hurricane intensity have not notably improved. Recent model results that incorporate the influence of the ocean are, however, very encouraging (e.g., DeMaria et al., 2005; Chen et al., 2006).

It is not certain that we will be able to significantly improve predictions of hurricane intensity and associated wind damage, storm surge, and other impacts. However, the high costs of hurricane damage motivate an increased effort. The cost of evacuation ahead of a hurricane has been estimated at $1M per mile of coastline (Walter, 1999). The cost of shutting in production at oil and gas platforms is estimated at hundred of thousands of dollars per hour per platform (Perdue, 2006). The costs and disruptions due to unnecessary refinery shutdowns and the closing of other business activities add to the already significant direct and indirect hurricane costs. Clearly, the value of timely, accurate, and detailed hurricane forecasts is considerable.

Despite the growing importance to the Nation of improved hurricane forecasts, especially as they make landfall, funding for basic and applied hurricane research remains inadequate by at least an order of magnitude. An enhanced and concerted scientific research effort aimed at improving hurricane intensity prediction is required, building upon the last decade of planning by the hurricane research and operational forecasting communities (e.g. Marks, Shay and PDT-5, 1998). The research program proposed here should be linked with comparable efforts at translating actual intensity prediction improvements into more accurate and timely warnings for the public, and into more useful hurricane impacts prediction and planning.

Uncertainties that limit intensity prediction

The maximum potential intensity (MPI) of a hurricane has been estimated in consideration of atmospheric thermodynamics and dynamics, assuming that the surface temperature of the ocean below the storm remains a constant (Emanuel, 1988; Holland, 1997). The MPI can explain differences in tropical cyclone statistics between the tropical oceans. The MPI, however, has limited usefulness as a predictor of the intensity of individual hurricanes. Factors other than sea surface temperature are clearly important.

Although imperfect knowledge of large-scale environmental conditions limits intensity prediction skill, inadequate knowledge and understanding of the evolving internal structures of hurricanes and their interaction with the ocean (Shay et al., 2000; Bao et al., 2000; Bender and Ginis, 2000; Hong et al., 2000; Chen et al., 2006) is at least as responsible. These uncertainties can be categorized as 1) interior atmospheric dynamics and thermodynamics, 2) interior ocean dynamics, and 3) coupled ocean-atmosphere boundary layers.

The following physics are thought to be likely contributors to present intensity prediction limits, either because they are not included in current numerical models, or because the parameterization of their effects is inadequate or unknown.

Atmosphere

In the atmosphere, the major factors controlling hurricane intensity change include large-scale environmental vertical wind shear and moisture distribution (DeMaria 1996; Ortt and Chen 2004) and hurricane internal dynamics (e.g., eyewall replacement cycles and mesoconvective vortices). The lack of spatial resolution needed to resolve the eye and eyewall and inadequate physical parameterizations (e.g., microphysics and boundary layer) in the current numerical weather prediction (NWP) models are potentially responsible for the poor intensity forecasts. The RAINEX project has conducted observational and modeling studies aimed at understanding the eyewall replacement cycle. Cloud microphysics, electrification and lightning are aspects of tropical storms that may need to be better understood and modeled.

Ocean

The initial spatial distribution of potentially available heat content in the ocean is thought to be an important contributor to hurricane intensity changes. In many parts of the Gulf of Mexico, in the Caribbean Sea and along the eastern seaboard, strong upper ocean currents including the Loop Current, the Florida Current, and the Gulf Stream provide large quantities of heat to fuel hurricanes. These currents may vary strongly on time scales comparable to those of hurricanes, and their variations need to be forecast.

For predictive models of ocean heat content, the ocean state must be accurately initialized with satellite and in situ observations. Determining the most effective observational system depends on the particular methods and models used to estimate the ocean state, whether purely statistical or by data assimilation into a numerical model. Much research remains to be done on this aspect of hurricane prediction.

The actual heat content that is transferred to a particular storm depends on its motion and its strength. However, both positive and negative feedbacks to the storm may arise from dynamic and thermodynamic wake effects in the ocean. The upper ocean velocity and divergence fields below the storm are quite complex functions of time and space (Shay et al., 1998); as a result, one quadrant of the storm may be weakened while another is intensified.

A critical parameterization in the upper ocean is the vertical mixing scheme (Jacob and Shay, 2003), strongly affecting the distribution of sea surface temperatures and oceanic heat content during hurricane passage. If the scheme predicts too much mixing, entrainment cooling of the mixed layer reduces the flux of heat to the atmosphere causing the hurricane to weaken. Conversely, if the scheme does not allow adequate entrainment cooling, too much heat will be available for the air-sea fluxes and the storm will over-intensify. It is clear that the ocean and atmosphere boundary layers are strongly coupled, and they need to be properly modeled for improvements to intensity forecasts.

Coupled boundary layers and air-sea fluxes

The lower troposphere and upper ocean boundary layers are strongly coupled within hurricanes. This coupling gives rise to a number of potentially important feedbacks that may be involved in storm intensity changes. The Air-Sea Interaction Subgroup at the CBLAST Meeting in Miami (April 2005) concluded that further work is needed to improve parameterizations of air-sea fluxes, especially on the roles of wave field parameters, of breaking waves, and of spray. Further work on large eddy structures in the boundary layer, such as roll vortices, was also recognized as an important, but lower priority target.

The ocean wave field is intricately involved in the transfer of momentum between atmosphere and ocean, which must be well modeled to accurately account for the loss of momentum in the near-surface flow of the atmosphere (Moon et al., 2004a; Chen et al., 2006). This is clearly an important factor in determining possible storm intensity changes. The influence of the wave field on the heat and moisture fluxes is a factor that must also be considered (Bourassa, 2006). Accurate prediction of the evolving directional wave spectrum, including shallow water effects, is also critical for coastal inundation prediction.

A factor that has been completely neglected in hurricane models to date is the momentum flux due to rainfall (Caldwell and Elliot, 1971), which may contribute significantly to upper ocean currents. The surface wave spectrum is strongly affected by rainfall (Méhauté and Khangaonkar, 1990), but the effect has a wind speed dependency.

Boundary layer turbulence budgets within storms need to consider the impacts of stratification due to spray and bubbles. However, Kudryavtsev (2005) and Soloviev and Lukas (2006) concluded that the existing formulation of the sea-spray generation function underestimates the effect of spray buoyancy on the tropical cyclone boundary layer dynamics; a better understanding of the sea spray generation is required.

Emanuel (2003) proposed that spray production is the dominant factor for momentum fluxes at extreme wind speeds, and that the ratio of the drag coefficient and the exchange coefficient for specific enthalpy should become a constant. However, there are no observations of the spray production function. The spray droplet production function is hypothesized as a function of the wave spectrum (Andreas, 1998). Whitecap coverage has been related to the wind and wave field by Melville and Matusov (2002), but spray production is not simply related to whitecap area coverage. Observations of spray drop size density spectra are required as a function of wave breaking statistics and other boundary layer factors.

Spray contributions to latent and sensible heat fluxes and associated feedbacks have been modeled based on work by (Fairall et al, 1994; Andreas and Emanuel, 2001). Inclusion of spray improves comparison of hindcasts with observations (Li, 2004; Fairall et al. 2005; Ginis, 2005) Quantifying impacts and feedbacks depends on the fraction of droplets that fall back into the ocean before evaporating completely, but this is not known.

Boundary layer rolls appear in radar wind fields within hurricanes (Wurman and Winslow, 1998; Morrison et al., 2005). Their importance to boundary layer fluxes is unknown.

Inertial current shears and the upper ocean divergence field strongly contribute to the upper ocean boundary layer evolution, with associated controls on the total energy flux from the ocean to the storm. These dynamics are strongly affected by the background flow.

All of the factors and processes discussed above have not been adequately observed and measured and are likely to impact hurricane intensity prediction on a variety of time scales.

Strategy for reducing these uncertainties

The current approach of the USWRP involves enhancing regional atmosphere and ocean monitoring (especially ahead of storms), intensive observing periods (within and around storms), and coupled data assimilation and experimental forecasting (in conjunction with operational activities through the Joint Hurricane Testbed). This approach is sound, but it needs enhanced funding. Integration of these activities with a hurricane intensity process study is essential.

Modeling

A significant advance in numerical models of hurricanes has been made with the 2005 transition of the URI/GFDL coupled hurricane model to operational status at NCEP (Falkovich et al., 2005). Yet, there are important questions about the tuning of parameterizations, and even about the validity of the parameterizations in that model. To resolve the hurricane eye and eyewall structures crucial for intensity forecasting, the horizontal grid resolution may need to be at least ~1-2 km (Tenerelli and Chen 2002, Braun 2002, Rogers et al. 2003, Chen and Tenerelli 2006). The extreme winds, intense rainfall, large ocean waves, and copious sea spray push the surface-exchange parameters for heat, water vapor, and momentum into untested regimes. Some unresolved air-sea interaction processes (e.g. rain enhancement of momentum flux; spray and bubble influences on the turbulent kinetic energy budget) are not included, though there is reason to believe that they may play important roles within hurricanes. There is a need for a reinvigorated fully coupled atmosphere-wave-ocean modeling effort, closely coordinated with new observational efforts. Process modeling (e.g. LES and DNS) should be enhanced. Laboratory model experiments may be useful for understanding the wavy coupled boundary layer. Predictability studies are required to understand the fundamental internal and environmental limits of hurricane intensity prediction.

Observations

The USWRP strategy of aircraft-based hurricane observations, combined with land-based measurements within landfalling hurricanes, is sound and should be enhanced (Rogers et al. 2006). This includes aircraft deployable senor packages to measure the mesoscale upper ocean (temperature, salinity and current) and atmospheric fields (relative humidity, temperature and winds) and remotely sensed surface waves, winds, SSTs and surface currents. Intricate details of air-sea interaction within hurricanes cannot be studied from aircraft due to constraints on flight levels. The USWRP strategy must be significantly augmented with in situ, near-surface and upper ocean measurements. Unmanned aerial vehicles and balloons in the lower atmosphere, along with underwater gliders and floats for the upper ocean, are needed to quantify the connections between the ocean interior and the troposphere with the coupled ocean-atmosphere boundary layer. Critical measurements need to be made throughout, and adjacent to, the coupled wavy boundary layer. Needed observations include profiles of bulk variables (e.g. flow, temperature), turbulent kinetic energy and turbulent fluxes, wave properties including wave-breaking statistics, spray and bubble production functions, and the time- and space-varying spray and bubble size spectra. Atmosphere and ocean heat, moisture/salt and momentum budgets should be closed on the storm scale in order to provide the maximum constraint on model simulations.

The optimal mix of these measurements will of course depend on the projected storm paths relative to ocean features in the basins based on satellite-derived and model fields during the hurricane season (Shay et al. 2005). A series of intensive observation periods over several years to build a sufficient database of ocean, interfacial and atmospheric fields is required, ultimately aimed at evaluating and validating the next generation hurricane intensity models without degrading track prediction.

Improved methods are required for operationally estimating storm structure and strength when aircraft penetration is not possible. This argues for a remote sensing component of the observational program.

Theory

There are a number of aspects of hurricane structure and intensity where theoretical advances are needed to guide the inclusion of additional processes in numerical models. One of the major challenges is to develop a new approach to modeling the coupled boundary layer within hurricanes. Monin-Obukhov similarity theory has been pushed beyond its useful limits: The concept of bulk parameterization of interfacial fluxes of heat, moisture and momentum breaks down when the interface is replaced by a wavy nephaloid layer of spray and bubbles at very high wind speeds (Emanuel, 2003; Makin, 2005). New techniques in numerical modeling will be useful in conjunction with such theoretical studies.

Need for an intensive process study of hurricane air-sea interaction

The Navy CBLAST program made important contributions to our observations within hurricanes (Black et al., 2006) and to hurricane modeling (Chen et al, 2006). Following on the 5-year, $5M CBLAST effort, it is clear that the magnitude of the problem of quantifying and modeling air-sea interaction in hurricanes requires an order of magnitude increase in resources. CBLAST was, in effect, a pilot program that now clearly defines the need for a more substantial investment in basic and applied hurricane research.

The following requirements for additional observations emerged from CBLAST data analysis and modeling (Shay et al., 2005):

- Sea spray profiles below 50 m
- Direct turbulent flux profiles
- Mean profile structures (by radius, quadrant, etc)
- Complete 2-D wave spectra and wave breaking statistics
- Accurate fields of rain rate
- Near surface bulk variables

We need to make observations of key processes in storms that are not now being made. This requires application of new technologies (e.g. the ET probe for measuring near-surface turbulence; LIDAR for measuring spray drop-size spectra), and new strategies for making measurements.

For quantifying processes that are affected by turbulence, many realizations are required to overcome its intermittent space-time distribution. An enhanced strategy for maximizing the numbers of high-quality observations within the limited number of storms each year is needed.

Intensive study of landfalling hurricanes is crucial, both for hurricane model improvement, and for impact modeling. However, the causes of very rapid changes as storms come ashore combine air-sea interaction and land surface effects. It is important, in any case, to study storms that are intensifying, and these are more often in deep water.

A focus of the intensive process experiment should be in the Gulf of Mexico, and assuming international participation in the study efforts, the Caribbean Sea. In the Gulf of Mexico, favorable ocean and atmospheric conditions usually occur within 48 hours of landfall as we observed during Katrina, Rita and Wilma in 2005. Thus, we suggest that the focus of intensive process experiments should be in the Gulf of Mexico. That is, once the hurricane in the Gulf of Mexico, it will make landfall. Surrounding the Gulf of Mexico and throughout the Caribbean Sea, there are large populations many strategic industries, and significant infrastructure at risk. Storms in the Gulf of Mexico specifically threaten oil industry operations, including drilling, production and refining. The oil industry has a lot to gain from improved hurricane forecasts. In return, production rigs offer stable platforms for potentially making critical observations within storms and near the sea surface.

Similarly, the major shipping interests and major ports in the Gulf of Mexico and the Caribbean Sea have a significant interest in early, accurate and comprehensive hurricane predictions. Finally, all the coastal communities, both in the United States and internationally, will continue to be a grave risk until such forecasting tools can be produced. While insurers and reinsurers also benefit from such efforts, only 20% of typical hurricane losses in the United States are insured. The remainder is mostly paid by the federal government who therefore has the most to gain from hurricane damages mitigation arising from improved forecasting tools (Barton, 2001).

Programmatic linkages

Federal Agency roles

The USWRP offers an inter-agency framework for cooperative atmospheric research on hurricanes with an appropriate focus on operations and applications. The National Ocean Partnership Program (NOPP) offers a comparable framework for inter-agency cooperation on related ocean research and applications. We expect that the National Science Board’s Hurricane Research Task Force will recommend an overarching hurricane research initiative appropriate to the mission of the National Science Foundation. Enhanced funding through Atmospheric Sciences (ATM), Ocean Sciences (OCE), and NCAR will energize the research community. Close coordination with NOAA will be required to enhance links with operational forecasting groups (NHC, NCEP/EMC), and with the Environmental Research Laboratories (AOML/HRD, ESRL). Coordination with the Navy (ONR, NRL, NAVOCEANO) will be important not only for research efforts, but also for Navy operational purposes.. Because of the large potential hurricane impacts on the Gulf oil industry, the Minerals Management Service should also play a role.

Roles of states and regional organizations

The coastal states affected by landfalling hurricanes obviously have a large stake in the outcomes of the proposed research program. They can contribute to the success of the program by facilitating deployment of observational systems for ongoing enhanced monitoring and for intensive observational periods. Regional organizations, especially those involved in coastal ocean observations, can contribute significantly to the implementation of this program.

Roles of the commercial sector

The oil industry and the reinsurance industry are the largest commercial stakeholders in hurricane intensity forecasting improvement, for operational purposes and for long-term risk evaluation.

International Cooperation

Hurricane destruction, and the need for improved forecasts, is not limited to the U.S. Our neighbors to the south, especially Mexico, have suffered severely in recent years. Our Caribbean neighbors likewise will benefit from advances in numerical prediction of hurricanes. Japan has been heavily impacted by numerous typhoons during the past couple of years, and Australia was just hit with a category 5 storm. While not all affected nations will be able to contribute directly to the research effort, many could benefit from the training opportunities and research outcomes. Cooperation with our regional neighbors will potentially facilitate observational programs. To help initiate such international and national coordination, the interim project office will be established in Ft. Lauderdale (NSU).

Next steps

This draft program prospectus is being circulated widely among the tropical cyclone research community. An ad hoc science steering committee has been formed to revise this prospectus to take into account feedback from the research community. Funding for further planning processes will be sought, with the objective of developing a science strategy document by September 1st, and ultimately a science implementation plan.

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