Working Draft Report : 24 Aug 2005 LKShay

Air-Sea Interactions in Tropical Cyclones Workshop

Camp Springs, DC 24-25 May 2005

Preface:

This workshop was convened to address the near- and far-term theoretical, observing, and modeling challenges in developing the next-generation coupled ocean-hurricane prediction system to become operational at the National Weather Service/National Centers for Environmental Prediction (NWS/NCEP) during 2007. A broad cross-section of researchers, numerical modelers, operational forecasters, and managers of governmental and university research programs gathered at NCEP in May 2005 to identify the scientific challenges associated with coupled models and to discuss potential avenues for addressing those challenges.

The context for this workshop, in both the NWS and US Weather Research Program (USWRP) frameworks was provided by Steve Lord (NCEP/Environmental Modeling Center) and Naomi Surgi (NCEP/EMC). Nick Shay (Rosenstiel School of Marine and Atmospheric Science/University of Miami) provided the overall charge of the workshop, which is to assess progress in the Air-Sea Interaction Community based on field programs and modeling studies sponsored by National Science Foundation, Office of Naval Research and National Oceanic and Atmospheric Administration through the USWRP Hurricane Landfall program, and to identify pressing scientific issues related to improving the physics of the air-sea interaction problem under strong winds in a hurricane and forecast models. Central to this theme is how the forecasting community can use these data sets to improve predictions from coupled ocean-atmosphere models. A clear objective of the workshop was to open the dialogue between the forecasting and research communities, and understand each group's needs. Breakout groups were designed to maximize discussions between forecasters and researchers in addressing these cross-cutting issues.

To set the scene for the challenges that lie ahead, the workshop began with a series of overview presentations from NCEP-related activities: Operational Modeling (Surgi), Wave Modeling (Tolman), Ocean Modeling (Lozano), Data Assimilation (Derber), and Coupled Modeling (Ginis-University of Rhode Island). A recurrent theme was that any potential improvements for intensity forecasts must not degrade track forecasts. The two breakout groups in the afternoon focused on model forecasting and required observations. The second day focused on research issues and their importance for forecasting issues: Oceanic Observations (Shay-UM), Atmospheric Boundary Layer Observations (Barnes-University of Hawaii), Ocean Modeling (Jacob-University of Maryland-Baltimore County), and Sea Spray Parameterization Schemes (Fairall-Environmental Technology Laboratory). In addition, two brief talks were given by Girton (University of Washington-Applied Physics Laboratory) and Terrill (Scripps Institution of Oceanography) on profiling floats that were deployed in the ONR-Coupled Boundary Layer Air-Sea Transfer (CBLAST) program. This session emphasized the need for continued observations to improve our understanding of physical processes and model parameterizations prior to implementation in forecast models. The afternoon breakout sessions focused on setting priorities and refining focused recommendations discussed in Plenary on the first day.

A summary of the workshop presentations and findings is given in the following report: the key recommendations of the two working groups are presented first and this is followed by summaries of the individual presentations. The Appendices contain the workshop agenda, lists of workshop participants and working group members and discussions of individual break-out groups. We thank all of the contributors to this report, including all of the speakers and workshop attendees. Thanks to Steve Lord and colleagues at EMC/NCEP for providing the support for the workshop.

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Workshop Conveners June 2005

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Workshop Report and Overview

Executive Summary

The Weather Research and Forecast (WRF) system is currently under development by the U.S. weather research and operational modeling communities. The WRF will replace current mesoscale modeling capabilities for various mesoscale forecast applications at operational Numerical Weather Prediction centers including NCEP and AFWA beginning in 2004. The WRF for hurricane forecasts (HWRF) will replace the Geophysical Fluid Dynamics Laboratory hurricane prediction system at NWS/NCEP and will be coupled to the Hybrid Community Ocean Model (HYCOM) in 2007. This coupled system will serve as the nation's next-generation operational hurricane prediction system, as well as serve as the primary research hurricane model.

Although significant progress has been made over the past several decades in advancing our nation's hurricane track forecasting capability, scientific and forecast challenges remain that need to be addressed by the next-generation coupled ocean-wave-atmosphere hurricane prediction system, which includes understanding the role of the upper ocean on hurricane intensity through the air-sea interface and the atmospheric boundary layer. Given a spectrum of differing track scenarios such as erratically moving storms, storms that accelerate, and storms that stall, any improvements to the hurricane intensity forecast must not degrade track forecasting. In the case of a tropical cyclone interacting with the upper ocean, any subsequent intensity change is sensitive to the track forecasts. Notwithstanding, when the forecast track is fairly certain within 36 hours of landfall, understanding the ocean's role on the intensity change through air-sea interactions becomes of paramount importance as deep ribbons of high oceanic heat content water surround the US coastline. By providing better initial conditions ocean conditions, and improving air-sea parameterization schemes in the coupled models, we may expect improved forecast of the tropical cyclone surface wind field, the ensuing storm surges and the inland flooding, which accounts for a majority of the Nation's hurricane-related fatalities.

To meet these forecast challenges, significant advances must concurrently occur in observations, data assimilation techniques; and model development for both the hurricane environment and the hurricane core to properly simulate the complex interactions between the physical and dynamical processes on different scales of motion that determine the hurricane motion, and to forecast intensity changes over the open and coastal ocean during hurricane landfall. The HWRF will be a high-resolution, coupled air/sea/land hurricane prediction model with advanced physics. Other planned advancements in the HWRF system include a local advanced atmospheric data assimilation capability to address the next generation initialization of the hurricane-core circulation. It is envisioned a similar process must occur for oceanic data assimilation on the basin scale, such as from the ongoing Global Ocean Data Assimilation Experiments (GODAE).

The U.S. Weather Research Program (USWRP) was designed to bring together researchers and the operational community to meet such challenges as these. It is under the auspices of the USWRP that this workshop was convened to begin discussing: (1) the state-of-the-art in tropical cyclone models and observations; (2) maximizing the usefulness of various data sets that have been acquired by various groups in hurricane environments over the past five years (ONR CBLAST in multiple hurricanes; NSF/NOAA Experiments in Isidore and Lili; NRL in Ivan; MMS in Georges, etc); and (3) upper-ocean observational strategies to acquire more complete data sets that must now include ocean current and salinity profiles as well as thermal profiles to evaluate the oceanic and coupled forecast models.

One of the key impediments that must be addressed by the community is to provide a comprehensive data archive to support the operational implementation of the HWRF in the 2007 time horizon. Specific attention must be directed toward improving air-sea parameterizations (such as drag and enthalpy coefficients), and to assess the relative importance of sea spray under fetch-limited wave fields. The development and testing of air-sea parameterizations at high wind speeds are required for the tropical cyclone forecast problem for both the large-scale environment and on the tropical cyclone scale. These were the overarching objectives presented to the broad cross-section of researchers, modelers, operational forecasters, and physicists, and managers of governmental and university research programs who gathered at the NCEP in May 2005.

Break-out groups purposely included both forecasters and researchers to deal with cross-cutting ocean-atmosphere issues. Each group focused on the same sets of questions with the intent to recommend a set of priorities to deal with the coupled ocean-wave-atmosphere part of the forecast models. Within the broad framework of ocean-atmosphere coupling, the central questions posed to each breakout group were:

1. What is the current *state-of-the-art* in observations and models for the tropical cyclone problem, and how can this community maximize recently acquired data sets?
2. What relevant time-space scales need to be resolved to improve intensity predictions in the models and what observations are needed to evaluate them with regard to vertical mixing, wave coupling, and air-sea parameterizations?
3. What metrics need to be in place for assessment of model-generated fields, and how do we implement them in near-real time for forecasting needs?
4. What is the design of an optimal field program for the evaluation of these models fields for *in situ* and satellite-based support? How can the community maximize the Global Ocean Observing System data to steadily improve ocean models?

A benefit of this approach was a similar set of recommendations were determined from both break-out groups. That is, a consensus was reached from the more than 30 participants. In addition, the informal exchanges between forecasters and researchers will inevitably foster collaborations. Such collaborative ties between academia, government, and private sectors are central to advancing our understanding of the tropical cyclone intensity forecast problem and achieving the NCEP goal of having a fully coupled HWRF/HYCOM model for operations.

Breakout Group Recommendations:

Both working groups agreed that infrastructure and resources need to be developed over the next three years. Specific recommendations are:

1. Given the range of uncertainty in the surface drag (e.g., wave effects), heat fluxes (e.g., sea spray), and initial conditions (e.g., wind field) beyond 30 m s^{-1} using CBLAST data, assess how these uncertainties propagate through the coupled GFDL/HWRF model;

2. Develop an archive of data sets and model outputs and make these archives publicly available for research and operational purposes. Investigate the potential use of these data sets in assimilation, evaluation, and verification of models and parameterization schemes (e.g., HYCOM);

3. Create an in-situ tropical cyclone ocean-atmosphere observing program for pre-storm, storm, and post-storm environments. Develop optimal observing strategies and observational mix for spatial evolution of upper ocean, interface, and atmospheric fields (including secondary circulations such as roll vortices in the hurricane boundary layer); and;

4. Develop improved ocean model initialization schemes through data assimilation of satellite and *in situ* measurements, and test mixing parameterizations for a spectrum of ocean, wave and atmospheric conditions including the impact of waves on the surface heat, moisture and momentum fluxes and thus on the evolving ocean mixed layer.

A recurrent theme in all of the discussions from both breakout groups was that this program needs to build on recent field programs such as ONR-CBLAST experiments in multiple years and NSF/NOAA in Isidore and Lili. In this broader context the background and justification for each of these four recommendations is provided in the following four subsections.

1. Air-Sea Parameterizations

A central issue in the air-sea interaction parameterizations is the appropriate value for the surface drag coefficients during high winds. It is clear from the recent experimental data that the drag coefficient does not continue to increase *ad-infinitum* with winds. Several investigations have shown that the coefficient seems to have a maximum between 28 to 32 m s^{-1} with values of 2.5 to 3.5 x 10^{-3}. These investigations range from using Global Positioning Sondes (GPS) sonde wind profiles extrapolated to the surface, wind-wave tank results, turbulent flux measurements, numerical modeling results with coupled wave-atmospheric models and using forced upper ocean currents as a tracer of momentum flux. While the air-sea community agrees on the leveling off of surface drag values, what remains unclear is whether the drag decreases with higher winds or remains relatively constant. Measurements must be acquired on the right side of the storm where the wind and waves are presumably interacting with the ocean current field to impact the momentum flux and the surface drag, which then feeds back to hurricane intensity.

Another critical issue is the role of sea spray in high winds, and especially thermodynamic effects of the evaporation of spray in the tropical cyclone boundary layers. Three important parts in understanding the impact of sea spray are: 1) size spectrum characterization as a function of forcing (stress, wave breaking, etc); 2) exchanges of heat and moisture with an initial state at rest; and 3) sub-grid scale distortion of the surface layer temperature and moisture structure by droplets. Of particular interest is the feedback mechanism that characterizes the manner in which the various sizes of evaporating droplets modify the stratification near the oceanic surface layer, which reduces further droplet evaporation, but enhances the sensible heat fluxes. This approach introduces tuning coefficients based on the ratio of the enthalpy flux and surface drag coefficient that are a function of tropical cyclone intensity. For a high-droplet source function, this ratio decreases in the current version of the model. To get the impact of sea spray correct, measurements in the surface layer (~50 m) are required that include turbulent fluxes, mean profile structures, wave spectra, wave breaking and accurate estimates of rain rates. Measurements at 50-m levels may not be attainable from the NOAA WP-3D aircraft, but perhaps a sensor package could be potentially developed for a Unmanned Aerial Vehicle (UAV) to address this scientific question (see ftp://ftp.etl.noaa.gov/user/cfairall/onr_droplet/parameterization/).

In a broader context, the ONR-CBLAST data must be used to examine the sensitivity of the model simulations to these parameterizations. This modeling-based approach would provide insights into the parameter space of these important air-sea processes where data in the atmospheric and oceanic boundary layers can be used to constrain model solutions. This would lead to an understanding of uncertainties in observations and provide a motivation for the next series of field experiments discussed below.

2. Data Archive

The breakout working groups agreed that coupled ocean-atmosphere data sets must be archived and maintained for the community for use in model evaluation studies (the evaluation step is considered to come before the validation step). Such data sets must include:

1. Josephine (1984) and Gloria (1985) current and temperature profiles from the Ocean Response to a Hurricane (ORTAH) project;
2. Gilbert (1988) current and temperature profiles prior, during, and subsequent to the storm from the ONR/NOAA project;
3. Dennis (1999) ocean mixed layer float data acquired prior, during, and subsequent to the storm for an NSF project;
4. Georges (1999) current and temperature profile data acquired prior, during, and subsequent to the storm for an Minerals Management Service (MMS) project;
5. Isidore and Lili (2002) current, temperature, and salinity profiles acquired prior, during, and subsequent to the storm for an NSF/NOAA project;
6. Frances (2004) current, temperature and salinity profiles acquired prior, during and subsequent to the storm for the ONR CBLAST project; and
7. Ivan (2004) current, temperature, and salinity data acquired prior, during and subsequent to the storm for an NRL project in the northern Gulf of Mexico.

In summary, only in a few storms have ocean current and shear structures been observed over the past 21 years from aircraft campaigns. Moored measurements during Georges and Ivan were fortuitous encounters, as opposed to focused aircraft-based experiments in CBLAST and NSF/NOAA programs. Given its importance for shear-induced mixing processes (Richardson number instabilities), this relatively poor data base needs to be improved to advance coupled modeling during hurricane conditions.

These data sets, along with surface forcing from remote sensors (both satellite- and aircraft-based), GPS sondes and available wave data should have a permanent archive site where the community can access these valuable data sets. The NDBC surface buoy data and thermal profiles from Airborne eXpendable Bathythermographs (AXBT) from decades of measurements must be included in such an archive. The archive should also include model-generated fields from GFDL that could be used by graduate students for their thesis/dissertation research. As noted in both breakout groups, this will require resources to establish the archive, locate the data and establish quality controls, and maintain it perhaps on a password basis for investigators working with NCEP. This effort will require a full-time position for a couple of years to establish it.

3. Sampling Approach

In support of these recommendations, and the recent successes of the ONR CBLAST and the NSF/NOAA program, the minimum sampling approach must include pre-storm, during and post-storm measurements to understand the impacts of the ocean forcing on the atmosphere, and the oceanic response to the tropical cyclone forcing. Specifically, the required types of observations and platforms to address this problem are:

1. Pre-storm survey (oceanic temperature (T), velocity (u,v) including shear, salinity (S), pressure (p)) using a combination of Lagrangian floats and drifters, and aircraft expendables. These ocean measurements should be at least through the main thermocline (upper 250 m or deeper in warm ocean features) and preferably to as deep as 1000 m to resolve the background flows through the dynamic height field. Boundary layer structure must also be observed with GPS sondes and remote sensors such as the Stepped Frequency Microwave Radiometer (SFMR);

2. Storm survey (T, u, v, S, p) from floats and drifters, and expendables profiling through at least 250 m; wave measurements from floats and aircraft remote sensors; boundary layer structure from GPS sondes; surface winds from Lagrangian drifters and aircraft remote sensing; sea-spray down to 50 m; and turbulence flux profiles from aircraft-based (or UAV) measurements; and,

3. Post-storm (T,u,v, S, p) from floats and drifters, and expendables over the domain of the storm survey; surface wave and wind measurements from floats and remote sensors; and GPS sondes for the atmospheric boundary layer structure.

This approach emphasizes observations over both space and time using floats, drifters, and expendables that are capable of measuring current, temperature, and salinity. What is lost in time from the spatial snapshots from the aircraft is gained by high time resolution in floats and drifters. Thus, the measurement approach emphasizes flexibility to optimize the data acquisition efforts since no single approach will resolve the coupling issues.

Upper-ocean measurements of T, u, v, and S should have a vertical resolution of less than 4-m to accurately estimate current shears and Richardson numbers and the floats should measure these profiles at least at hourly intervals. In terms of horizontal resolution during the storm, the oceanic and atmospheric profiles should be spaced no more than 0.5 radii of maximum winds (Rmax). Remote sensing and flux measurements must be as rapidly as possible.

For non-events and more routine measurements for model evaluation and validation of the basic state of the ocean, both groups recommended enhancements to the NDBC buoy program to measure temperature and current profile time series, surface wind stress and directional surface waves; continued enhancements of the ARGO/Electro-Magnetic Autonomous Profiling EXplorer (APEX) floats (including mixed layer floats) and drifters as part of Integrated Ocean Observing System (IOOS); utilization of the growing network of High Frequency (HF) Coastal Radars deployed as part of the Coastal Ocean Observing System (COOS) to measure currents, waves and winds; and NWS WSR-88D radar networks.

4. Ocean Model Initialization and Mixing Parameterizations:

Based on recent findings, particularly in the Loop Current and warm core ring complex in the Gulf of Mexico, initializing ocean models with the correct background states represents a challenge for the modeling community. To improve the understanding of the role of the upper ocean on tropical cyclone intensity, the background state must be specified with the correct thermal and density structure that will then give rise to ocean features where energetic currents occur along frontal boundaries. Such features include the Loop Current, Florida Current and Gulf Stream which lead to the transport warm, high oceanic heat content from the tropics to the mid-latitudes as part of the climate cycle. One method is adjusting the model is through data assimilation of the sea-surface height from satellite radar altimetry and sea-surface temperature fields and projecting the surface height field vertically as is currently done in the HYCOM model. In many instances, this approach has worked reasonably well. However, assimilating T/S profiles from float data (or other routine measurements) is an opportunity that must be fully explored to get the correct basic state in terms of the thermal, haline, density and velocity structures. Time-dependent behavior of these warmer oceanic features (significantly reduced negative feedback to the hurricane) must also be evaluated with these data sets to ensure that the initial model fields are correct prior to the passage of a tropical cyclone.

A second important issue deals with the oceanic mixing parameterizations in ocean models. Given the number of mixing schemes available at the present time, choosing the most appropriate scheme for an oceanic or coupled system requires careful examination of simulated fields with observed profiles to understand the sensitivity of the oceanic response to these mixing schemes. With the exception of the bulk schemes, the turbulent kinetic energy schemes depend primarily on shear at the base of the oceanic mixed layer to parameterize entrainment heat flux. This shear term has been shown to contribute between 60 to 80% to the observed oceanic mixed layer cooling in predominately negative feedback regimes (away from frontal boundaries). Vertical shear effects in the ocean are similar to those of atmospheric shear, although the shear must be calculated over much smaller vertical scales. Large values of ocean shear, will lower the Richardson numbers to below criticality, and force the upper ocean to mix and cool. Recent simulations from each of these schemes has shown that for the same initial ocean conditions and same forcing, the amount of cooling in the ocean mixed layer differs considerably in terms of magnitude and structure. The amount of ocean cooling impacts the available air-sea fluxes that provide heat and moisture for the storm. The amount of uncertainties in surface fluxes from these various mixing parameterizations is unacceptable for an ocean model or fully coupled system because they will lead to larger uncertainties in intensity and structure of a tropical cyclone. In addition, the oceanic mixed layer heat, mass, and momentum budgets are affected by advection of the gradients in frontal regimes due to the background and wind-forced currents. In these cases, the oceanic mixed layer budgets are not 1-D, rather they are 3-D. Thus, careful attention must be devoted to mixing schemes and considerably more current and shear data are required to represent parameter space for oceanic models.

Little attention has been given to the impact of the surface wave interactions with the surface current field, and the impact of the wave coupling on the oceanic mixed layer processes through breaking waves. For example, in strong oceanic current regimes, the vorticity field associated with background and wind-forced currents will impact the surface waves through wave-current interactions. This may have a positive or a negative impact on air-sea fluxes depending on whether the wave heights are increased (caustics) or decreased (shadow region). To investigate such interactions numerically and their possible impact on air-sea fluxes will require much higher resolution Large Eddy Simulation (LES) oceanic models similar to those developed in the CBLAST program.

Air-Sea Interactions in Tropical Cyclones Workshop
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Final Report

1.0 **Welcome, Introduction and Purpose of the Workshop (Stephen Lord/Naomi Surgi, NWS Environmental Modeling Center)**

This workshop was convened to address the near- and far-term theoretical, observing, and modeling challenges in developing the next-generation coupled ocean-hurricane prediction system to become operational at the National Weather Service/National Centers for Environmental Prediction (NWS/NCEP) during 2007. A broad cross-section of researchers, numerical modelers, operational forecasters, and managers of governmental and university research programs gathered at NCEP in May 2005 to identify the scientific challenges associated with coupled models and to discuss potential avenues for addressing those challenges.

The context for this workshop, in both the NWS and US Weather Research Program (USWRP) frameworks was provided by Steve Lord (NCEP/Environmental Modeling Center) and Naomi Surgi (NCEP/EMC). Nick Shay (Rosenstiel School of Marine and Atmospheric Science/University of Miami) provided the overall charge of the workshop, which is to assess progress in the Air-Sea Interaction Community based on field programs and modeling studies sponsored by National Science Foundation, Office of Naval Research and National Oceanic and Atmospheric Administration through the USWRP Hurricane Landfall program, and to identify pressing scientific issues related to improving the physics of the air-sea interaction problem under strong winds in a hurricane and forecast models. Central to this theme is how the forecasting community can use these data sets to improve predictions from coupled ocean-atmosphere models. A clear objective of the workshop was to open the dialogue between the forecasting and research communities, and understand each group's needs. Breakout groups were designed to maximize discussions between forecasters and researchers in addressing cross-cutting issues.

To set the scene for the challenges that lie ahead, the workshop began with a series of overview presentations from NCEP-related activities: Operational Modeling (Surgi), Wave Modeling (Tolman), Ocean Modeling (Lozano), Data Assimilation (Derber), and Coupled Modeling (Ginis-University of Rhode Island). A recurrent theme was that any potential improvements for intensity forecasts must not degrade track forecasts. The two breakout groups in the afternoon focused on model forecasting and required observations. The second day focused on research issues and their importance for forecasting issues: Oceanic Observations (Shay-UM), Atmospheric Boundary Layer Observations (Barnes-University of Hawaii), Ocean Modeling (Jacob-University of Maryland-Baltimore County), and Sea Spray Parameterization Schemes (Fairall-Environmental Technology Laboratory). In addition, two brief talks were given by Girton (University of Washington-Applied Physics Laboratory) and Terrill (Scripps Institution of Oceanography) on profiling floats that were deployed in the ONR-Coupled Boundary Layer Air-Sea Transfer (CBLAST) program. This session emphasized the need for continued observations to improve our understanding of physical processes and model parameterizations prior to implementation in forecast models. The afternoon breakout sessions focused on setting priorities and refining focused recommendations discussed in Plenary on the first day.

Steve Lord and Naomi Surgi welcomed the participants scientific meeting on the HWRF modeling system. The overall WRF program is to provide the community with a full-range of Numerical Weather Prediction (NWP) model capabilities that include such things as model software architecture and physics, data assimilation, input/output applications interfaces, testing and verification, documentation, standards, as well as a framework within which to develop and test new theories, models, and capabilities. The WRF is a community effort that provides a modeling infrastructure to run on a number of platforms such as the IBM at the National Center for Atmospheric Research (NCAR), Alpha-Linux system at the Forecast Systems Laboratory (FSL) , and Linux PC systems. The WRF-community based models will be available to both university and governmental organizations.

Within the overall WRF activities, the hurricane modeling system is a particular subset with unique characteristics and issues. The HWRF will be a coupled land/sea/atmosphere model. The HWRF will have a nested wave model coupled to the ocean model, and the land surface model will be coupled to hydrology to address the inland flooding problem. Development of this advanced hurricane modeling system will provide a unique opportunity for collaboration between the research and operational communities to take advantage of a variety of expertise that is necessary for the successful modeling system development.

Lord and Surgi challenged the workshop participants to consider the data needs for such a hurricane prediction system – including assimilation issues, as well as considering the configuration of the optimal coupled land/sea/atmosphere model for the hurricane forecast problem, and any roadblocks to achieving either the data or modeling goals. They charged the workshop participants with beginning to design, through working group sessions, a pathway to implementation of the next-generation hurricane forecast model.

2.0 Summary of ONR CBLAST April 2005 Workshop (P. Black)

The ONR CBLAST workshop was held 4-6 April 2005 in Miami and brought together scientists involved in the CBLAST field and modeling studies under the sponsorship of ONR and NOAA. The goal was to discuss the progress from the field campaigns and ongoing model studies largely focused on the Isabel (2003) and Frances (2004) cases. Presentations and summaries from the breakout groups can be found at: http://www.aoml.noaa.gov/hrd/CBLAST/CBLAST4.html. Two important findings from that workshop are:

1. Upper ocean floats such as ARGO-Solo and the electromagnetic APEX floats developed by SIO and WEBB and UW/APL, respectively, worked well in the hurricane environment by providing measurements of T, S, u, v (current) profiles, waves and acoustical properties for the first time; and

2. Model studies are suggesting a new wind-wave coupling parameterization in which the behavior of the drag coefficient levels off between 28 to 32 m s^{-1} with a range of values ranging from 2.8 to 3.5 x 10^{-3} at 40 m s^{-1}.

Direct measurements of the air-sea fluxes during the CBLAST storms were valid for winds to 30 m s^{-1} measured in the left-front quadrant of a tropical cyclone. It is encouraging that several studies are showing this leveling off, and not a continued increase of the drag coefficient with surface winds as suggested by earlier drag coefficient parameterizations. In a broader context, the ONR-CBLAST data in must be used to examine the sensitivity of the model simulations to these parameterizations. This modeling-based approach would provide insights into the parameter space of these important air-sea processes where data in the atmospheric and ocean boundary layers can be used to constrain model solutions. This would lead to an understanding of uncertainties in observations and provide a motivation for the next series of focused field experiments.

3.0 Summary of Presentations

A. Forecaster Overviews:

A.1 Operational Modeling at NCEP (Naomi Surgi, EMC/NCEP)

Naomi Surgi gave an overview of the progress on the Weather and Research Forecast system for hurricane prediction, e.g., the HWRF scheduled for operational implementation at NCEP in 2007 when it will replace the current GFDL model. This advanced hurricane prediction system is being developed at the NWS/NCEP's EMC to address the nation's next-generation hurricane forecast problems. The HWRF will have the capability to fully address the intensity, structure, and rainfall forecast problem in addition to advancing wave and storm surge forecasts. As continued advancements in track prediction will remain an important focus of this prediction system, any new enhancements for physical processes to improve the intensity and structure forecasts cannot be implemented if they degrade track forecasting.

The HWRF will be a high resolution coupled air-sea-land prediction model with a movable nested grid and advanced physics. To address the totality of the hurricane forecast problems noted above, the HWRF will also include coupling to an ocean surface wave model that will eventually be coupled to a dynamic storm surge model. To facilitate these requirements, the HWRF will incorporate advanced air-sea physics of the atmospheric and oceanic boundary layers. Additionally, the land-surface component will also serve as input to hydrology and inundation models to address to hurricane-related inland flooding problem. For initialization of the hurricane core circulation, an advanced data assimilation technique is under development at EMC that will make use of real-time airborne Doppler radar data from NOAA's high altitude G-IV jet to initialize the 3-D storm-scale structure.

A.2 Surface Wave Modeling at NCEP (Hendrik Tolman, NCEP)

This presentation consisted of four parts. First, a general review of common wind-wave modeling practices was given. Second, a brief overview of WAVEWATCH III was given that covered its history, and its main features (numerics, physics, island blocking). Third, operational models at NCEP were discussed where special attention was focused on hurricane wave models, and on the quality of the hindcasts and forecasts. Finally, future plans were discussed that focused on hurricane wave prediction, e.g., the development of a multi-scale wave model, new approaches to nonlinearities in the wave model, and physics of wind-wave interaction at high wind speeds.

Since 1994, NCEP has been running a third-generation ocean wave model. The decision was made to build a new model termed WAVEWATCH based on the WAM, but with significant differences. WAVEWATCH became the operational ocean wave model in 2000. WAVEWATCH is initialized by global model winds and has versions customized for the western North Atlantic and the eastern North Pacific Ocean. All of the models use 24 directions and 25 frequencies for wave forecasts. Some aspects of the models must be parameterized due to the lack of both computing power and physics limitations. For example, capillary waves are critically important, but are not included in the dynamic model and must be parameterized.

Hourly wind fields are essential to forecast the wave field development, especially for rapidly moving, intense, small-scale hurricanes. Hourly wind field analyses were implemented in 2002 for the Atlantic hurricane season. Such hourly analyses are necessary to ensure continuity of the wave model and for swell forecasts. The ocean and atmosphere are coupled through various fluxes that are also a function of surface waves. Some examples of the coupling are:

1. Momentum is transferred from the atmosphere to the ocean by surface stress and subsequent wave actions.

2. The wave breaking and spray influence the fluxes of mass and heat.

3. Wave breaking also is a large source of turbulent energy in the upper ocean and the momentum in the waves is released during the breaking action.

One of the scientific issues that needs serious attention is that the momentum transfer and drag coefficients included in the models are extrapolated from moderate wind conditions. Information is not available at the low and high ends of the wind velocities. The errors introduced by this extrapolation have a first-order impact on wave growth rates.

A.3 Operational Ocean Modeling at NCEP (Carlos Lozano, NCEP)

High-resolution ocean forecast systems for nowcast and short term (5 days) forecast in the Atlantic and the Pacific Ocean basin will form the backbone for the regional ocean model components of the coupled hurricane models. The ocean forecast system for the Atlantic Ocean basin (25^{o}S-76^{o}N) is being prepared for daily oceanic operations with resolution of ~5 to 7 km along the path of most hurricanes. Hindcast ocean simulations (uncoupled) during Isabel and Frances hurricanes illustrate the advantages of a high-resolution ocean model to capture sea surface temperature cooling due to turbulent mixing and near-inertial pumping on the thermocline. Initial ocean conditions will be provided by operational nowcasts that will include the assimilation of SST (remotely sensed and in situ), sea surface height anomalies from altimeters (Jason, GFO, etc), and *in situ* temperature and salinity observations (CTD, AXBT, buoys and drifters). There is a clear requirement for comprehensive ocean and atmosphere observations in a storm-coordinate system to evaluate coupled hurricane models, and for the development of efficient deployment strategies that provided these gridded observations.

A.4 Data Assimilation Efforts at NCEP (John Derber, NCEP)

The basic objective of the NWP data assimilation is to combine all relevant information from any source to produce an estimate of the most likely state of the atmosphere at the beginning of the forecast cycle. Generically, the "cost" or "fit" function optimizes the fit of the background field with the observations and other constraints. In some data-sparse areas of the world, the background field is as good as the observations.

1. The first step is to convert the analysis (background field) to observation-like information and compare that information to observations. Forward models to make the conversions can be such things as a simple interpolation scheme, a complex radiative transfer function, or a precipitation algorithm.

2. The weights given to the various terms in the equations are related to the estimates of the error covariances.

3. The final terms are lumped under "other constraints", for example, to force the moisture values to be non-negative, and keep a balance between the mass and momentum in mid-latitudes. Significant differences exist in the data assimilation issues for large-scale processes in the tropics and for hurricanes. For the most part, the issues are mesoscale or smaller in nature. Clearly, data assimilation for hurricanes is much more difficult than for the larger-scale tropical circulations.

Some of the data assimilation challenges for the tropics and hurricanes include:

1. **Balance equations**: In the tropics (and for mesoscale in general), balance is dominated by moist processes and is much more complex than for the larger scales. Failure to properly treat the balance issues will result in a rapid loss of useful information at the beginning of the forecast. The increase in non-linearity due to moist processes make the tropical/hurricane problem more difficult to solve.

2. **Analysis variables:** To accurately analyze variables in the tropics such as cloud liquid water and cloud ice, a balance has to be achieved and all the fields involved need to be initialized, which also means the surface and ocean fields must be correctly specified. The ability to achieve a realistic balance is not as straightforward as for the larger scales.

3. **Background error covariance:** For the tropics, it is essential to have circulation-dependent error covariances, but they are difficult to determine. For example, the structure of the background error covariances for cloud and surface fields are almost certainly to be dependent on small-scale dynamics that are not well known. Further, it is critical to include in the background error covariances the relationships between the variables (e.g., water vapor and clouds).

Significant progress has been made over the past 18 months in the development of the operational WRF 3DVAR data assimilation system. . The research state-of-the-art version of the WRF 3DVAR is scheduled for 2006. The advanced four-dimensional data assimilation (A4DDA) scheme is likely to be implemented by 2010. The coupled ocean model data assimilation will focus on:

1. Upper ocean and mixed layer as being of primary importance,

2. Skin temperature, which is a primary measurement from satellites,

3. Bulk water temperatures obtained from ship observations. The satellite retrievals are calibrated to the bulk temperature, and

4. Profiles of the thermal (and salinity) structure and mixed layer depth which are provided by floats and expendable conductivity temperature and depth probes.

In summary, the improved specification of the background error covariance has top priority and not all of the observations are useful. Significant progress over the last few years has been made in how to assimilate data from a wide range of sources. However, recent observations are still not being used to the maximum extent possible, and some new observations have not yet been incorporated into the data assimilation system. The task of achieving an effective data assimilation scheme for a new observational data set may be on the order of 1-2 years from the time the data are reliably available. Data assimilation systems can and should be as transportable to different platforms as are the models.

A.5 Coupled Modeling at URI/NCEP (Isaac Ginis, URI)

In 2001 the GFDL/URI coupled hurricane-model model was implemented at NCEP/EMC for operational forecasting in the Atlantic basin. Since then joint research efforts of the URI, GFDL, and NCEP scientists have been focusing on further improvements of the GFDL/URI model. In this presentation, the latest research and development efforts are highlighted.

1. New ocean model initialization method:

A new ocean data assimilation and initialization package has been developed to improve simulations of the Loop Current (LC) in the GFDL/URI operational coupled hurricane prediction system. This procedure is based on feature modeling and involves cross-frontal "sharpening" of background temperature and salinity fields according to data obtained in specialized field experiments. It allows specifying the position of the LC in the Gulf of Mexico using available observations. The new initialization procedure will be tested during the 2005 hurricane season in the Atlantic basin. It is planned for operational implementation in 2006.

2. Improving air-sea momentum flux parameterization:

In the GFDL hurricane model, the air-sea momentum flux is parameterized with a constant non-dimensional surface roughness (or Charnock coefficient, $z_{ch} = z_0 g / u_*^2$, where z_0 is the roughness length, u_* is the friction velocity and g is the gravitational acceleration) and the stability correction based on the Monin-Obukhov similarity theory, regardless of wind speeds or sea states. This parameterization assumes an increase in C_d with wind speed. However, a number of studies have suggested that the value of the Charnock coefficient depends on the sea state represented by the wave age. Lively debate is ongoing in the research community over this relationship. The major reason leading to the discrepancies among different studies is the paucity of in situ observations, especially in high wind speeds and young seas.

We investigated the Charnock coefficient under hurricane conditions using a coupled wind-wave (CWW) model that includes the spectral peak in the surface wave directional frequency from WAVEWATCH III and a parameterized high frequency part of the spectrum using a recently developed model. The wave spectrum was then introduced to the wave boundary layer model to estimate the Charnock coefficient at different wave evolution stages. We found that the drag coefficient levels off at very high wind speeds, which is consistent with recent field observations. The most important finding of this study is that the relationship between the Charnock coefficient and the input wave age (wave age determined by the peak frequency of wind energy input) is not unique, but strongly depends on wind speed. The regression lines between the input wave age and the Charnock coefficient show a negative slope at low wind speeds but a positive slope at high wind speeds. This behavior of the Charnock coefficient in high winds provides a plausible explanation why the drag coefficient under tropical cyclones, where seas tend to be extremely young, may be significantly reduced in high wind speeds.

3. Improving air-sea heat and humidity flux parameterization:

Heat and humidity flux parameterizations are a crucial factor in the hurricane-ocean coupling. In high wind conditions, heat and humidity exchange coefficients c_h and c_e can be directly related to the roughness lengths of temperature and water vapor (Z_T and Z_q). We have tested various parameterizations Z_T and Z_q in the GFDL hurricane model and found that for simulations of very intense hurricanes with maximum wind speeds exceeding 50 m s^{-1}, large values of C_H are necessary, with c_h/c_d >1. For example, testing the parameterization of Z_T and Z_q used in the GFS global model for Isabel (2003) indicates that the storm fails to intensify beyond 50 m s^{-1}, while the observed maximum winds reached about 70 m s^{-1}. It is possible that sea spray, which is neglected in these experiments, may provide an additional heat and moisture source.

4. Development of a coupled hurricane-wave-ocean model:

We have coupled the GFDL hurricane model, the Princeton Ocean Model (POM), and the WAVEWATCH III model with the URI wind-wave boundary layer model. The highest resolution of the model in the movable inner-most mesh is 1/12 degree. We have developed a movable nested grid configuration of the wave model. The inner mesh of higher resolution follows the storm center, as it is done in the GFDL hurricane model. It is a necessary step to reduce significant computational requirements of the WW3 model. Although the testing and evaluation of the new coupled system has just begun, the first numerical experiments show encouraging results.

B. Researcher Overviews:

B.1 Upper Ocean Observations (L. K. (Nick) Shay, UM)

Over the past two decades, it has been fairly well documented that ocean current and the shear field play an important role in cooling and deepening of the oceanic mixed layer (negative feedback regimes). By contrast where the ocean mixed layer (and depth of the 26°C isotherm) is deeper, the ocean current shears may not be large enough to significantly cool the upper ocean. Such positive (or less negative) feedback regimes, which provide more of a sustained heat flux to the atmosphere during hurricane passage, are usually associated with deep warm fronts and eddies that are often characterized as deep ribbons of high oceanic heat content water. That is, advection of thermal gradients by the strong currents may counterbalance upwelling and mixing effects and provide more heat to the atmosphere.

1. Thin Mixed Layers : (Negative Feedback):

In negative feedback regimes, wind-driven vertical current shear induces mixing of the oceanic mixed layer and top of the thermocline (i.e., entrainment heat flux). Strong shear events lower the Richardson number to below criticality and thereby cause the ocean mixed layer to deepen and cool as cooler water from the thermocline is mixed with the warmer ocean mixed layer water. In this case, the sea-surface temperature represents a proxy for the ocean mixed layer temperature even using crude bulk ocean mixed layer models. Thus, the available ocean heat content, which is defined as the amount of heat from the surface to the depth of the 26°C isotherm, decreases and then negatively impacts storm intensity.

Despite the importance on the physics of the air-sea interactions (available heat and moisture), only seven aircraft-based experiments have specifically focused on measuring current and current shear for this important aspect of the tropical cyclone-ocean interaction problem. Airborne eXpendable Current Profilers were first launched in 1984 and 1985 as part of an oil company-consortium initiative Ocean Response To A Hurricane Program (ORTAH) in Norbert (eastern Pacific Ocean), and Josephine and Gloria (western Atlantic Ocean). Since that experimental effort, AXCPs have only been deployed in Hurricanes Gilbert (1988), Isidore and Lili (2002). As described below, profiling floats with electromagnetic current and shear measuring capability were recently deployed in Frances, and measured strong near-inertial currents and vertical shears over several days in the cold wake region.

2. Deep Warm Mixed Layers: Positive Feedback

Coupled ocean-atmosphere measurements were acquired during an NSF/NOAA-sponsored Hurricane Air-Sea Interaction Experiment. Dual-aircraft experiments mapped 3-dimensional fields using expendable profilers (AXCPs, AXCTDs, AXBTs, GPS) deployed from NOAA research aircraft as Isidore and Lili moved into the Gulf of Mexico in September and October 2002. As the storms encountered the Loop Current, Isidore intensified to a category 3 and Lili rapidly intensified to a category 4 storm. Even at these levels of intensity, the upper ocean response was minimal SST decreases of less than $1^{o}C$ and ocean heat content (OHC) losses less than 10 KJ cm^{-2}. That is, advection of thermal gradients may have counterbalanced shear-induced mixing processes associated with forced near-inertial motions. In this positive (less negative) feedback regime, advection of the thermal structure by the strong currents has time scales of less than a day with large geostrophically balanced currents transporting high OHC water (150 KJ cm^{-2}) from the Caribbean Sea into the Gulf of Mexico to form the Loop Current core. As Lili moved northwest of the Loop Current, the upper ocean cooled by more than $2^{o}C$ with a net OHC loss of about 30 KJ cm^{-2} due primarily to shear-induced mixing across the base of a thin ocean mixed layer in the Gulf Common water. The storm subsequently weakened prior to landfall to a category 1 storm due in part to the entrainment of drier air as well as interacting with an ocean previously cooled by earlier tropical storms Hanna and Isidore.

Since PDT-5 report (Marks and Shay, 1998), only two focused oceanic and atmospheric experiments in hurricanes have measured current and shear along with temperature and salinity. While there have been fortuitous encounters where tropical cyclones have passed over mooring deployed in support of other experiments such as Frederic (1979), Allen (1983), Gloria (1985), Georges (1999) and Ivan (2004). Developing, evaluating, validating, and implementing accurate ocean/coupled models will require **a more systematic measurement approach** to accurately represent the response to the atmospheric forcing and understand the levels of negative (and positive) feedback to the atmosphere over the life cycles of several storms. Measurements of T,S and velocity (u,v) acquired in grids are needed for the models to adequately represent parameter space, assess the ocean mixing schemes, and evaluate performance. Without the current and shear measurements, models will not necessarily improve (i.e., thermal structure is not enough).

B.2 Atmospheric Boundary Layer Observations (Gary Barnes, UH)

Observations collected over the last decade with the NOAA-AOC aircraft (directed by members of the NOAA/AOML/ Hurricane Research Division and university investigators) and recent specific experiments such as CBLAST, supported by NOAA, NSF, and ONR are revealing fresh details of the hurricane boundary layer. The observations are the result of new aircraft deployment strategies and the interpretation of new instrumentation that includes the SFMR, Doppler, fast response wind, temperature, and humidity sensors, and especially the Global Positioning System (GPS) sondes. At this early stage, the GPS sondes have been exploited more than the other sensors. Over 300 hundred vertical profiles of wind speed in numerous hurricanes reveal that roughness length (and therefore the drag coefficient) does not continue to increase with increasing wind speed as previously believed. Above 35 m s^{-1} the drag coefficient remains constant. The profiles also identify that 10-m winds are typically 0.8 -0.9 of the wind maximum that is typically located 500 to 700 m altitude.

GPS sondes deployed in Hurricane Bonnie (1998) provided the first views of vortex-scale horizontal maps of temperature, specific humidity, equivalent potential energy, and radial and tangential wind components from 10 m to 2 km altitude. These maps have a variety of structures that include nonisothermal inflow to the eyewall, rapid moistening of offshore flow, and the depth and energy content of the inflow layer to the eyewall. An energy budget of the inflow reveals that the increase of energy occurs within 50 km of the radius of maximum winds, demonstrating the importance of understanding the air-sea fluxes in the inner core of the hurricane.

Profiles of potential and equivalent potential temperature have structures in the inner core of the hurricane that depart from the typical undisturbed tropical conditions. Positive lapse rates of equivalent potential temperature well below the mid-tropospheric minimum, moist absolutely unstable layers, very shallow mixed layers, and nearly saturated and super-adiabatic surface layers have been observed. The GPS sonde results have the potential to serve as a test field for the GFDL and HWRF hurricane models used for operational and research tasks. Comparisons between the model fields and the observations may ultimately lead to improvements in key parameterizations, and thus result in improved intensity forecasts.

B.3 Ocean Modeling (S. Daniel Jacob, UMBC)

Modeling and evaluation of the ocean response to tropical cyclones are crucial to coupled hurricane intensity prediction. Since the ocean component in the prediction system provides the lower boundary conditions that affect the fluxes for rapid intensification or weakening. This overview focused on uncertainties in the state-of-the-art ocean response models from a physical and numerical perspective and their applications to coupled prediction system. Due to the availability of observations prior, during, and after the passage of the storms, simulations were conducted for Gilbert (1988), Isidore and Lili (2002) using the Hybrid Coordinate Ocean Model (HYCOM) to quantify the range of uncertainties relevant to coupled modeling.

1. Model and Simulations:

Two configurations of HYCOM were used to simulate the upper ocean response to hurricanes Gilbert, Isidore and Lili for different vertical resolution. Since Isidore and Lili occurred closely spaced in time, these two were combined into a 20-day simulation in contrast to a 6-day simulation in the Gilbert case. Momentum forcing in this study was derived by combining environmental winds from an atmospheric general circulation model with aircraft-reduced and buoy-observed winds using the Hurricane Research Division wind analysis program. While realistic initial conditions for the Gilbert case were derived from in situ data, background fields from a data assimilative basin-scale HYCOM run provide the conditions in the Isidore and Lili cases. Numerical simulations were conducted to quantify uncertainties for realistic and quiescent initial conditions and differing entrainment mixing schemes that parameterize sub-grid scale processes. Initial conditions were evaluated with data acquired one day prior to the storm passage.

2. Results:

Realistic initial conditions for the three cases considered here included the deep warm layers of the western Caribbean Sea, Loop Current, and the Warm Core Rings that separate from it in the Gulf of Mexico. Evaluation of initial conditions in the Gilbert case indicates that they are reproduced accurately for ocean response modeling. While the location of oceanic features are reproduced by the assimilative basin-scale model and the vertical thermal structure is comparable to Levitus and GDEM climatologies, pre-Isidore expendable probe data indicate a much warmer upper layer in the ocean. Consequently, simulated cooling is more than the observed cooling by about 0.5° C. This result highlights the need for routine pre-storm observations for evaluation of initial conditions used in the ocean component of the coupled model.

While the magnitude of upper-ocean cooling simulated for quiescent initial conditions compares reasonably well with observations, the pattern and extent of simulated cooling are modulated by pre-storm mesoscale variability. While attempts were made in the current ocean component of the operational coupled model to prescribe a condition that resolves the Gulf Stream system, the Loop Current eddies are not initialized in the present system. Results from Gilbert simulations suggest eddies are a necessity for more accurate prediction of the upper-ocean heat content evolution in the Gulf of Mexico. An additional effect of the pre-storm velocity structure is to reduce the frequency of the near-inertial internal waves generated by the storm and therefore the phasing of strong shears contributing to significant mixing will be delayed and make larger more fluxes available to the atmosphere.

One of the significant effects on the upper-ocean heat budget and the fluxes to the atmosphere is the choice of entrainment mixing parameterization. For quiescent initial conditions, the range of fluxes in the directly forced region of the storm exceeded 500 Wm^{-2} for different schemes. Comparative statistics suggest that the three higher-order mixing schemes considered will lead to a more accurate ocean response simulation. These comparisons are limited by data availability, and therefore routine measurements are necessary to evaluate the ocean component of the coupled system. Similar to the post-season track and intensity verification analysis, more ocean observations must be acquired to evaluate the different schemes on a post-season basis to build a statistical base of comparisons. Given the large range in the simulated surface fluxes for different schemes, this is a crucial step toward reducing this uncertainty. The approach of stand-alone ocean simulations using derived realistic atmospheric forcing used here allowed us to focus on and evaluate the ocean model and associated parameterizations. Since the boundary layer structure forcing from the atmospheric component of the coupled model is subject to additional uncertainties, this approach based on observations will lead to reduction in uncertainties of the ocean component in the coupled system.

B.4 Sea Spray Parameterization Schemes (Chris Fairall, NOAA ETL)

For the last decade, the NOAA Environmental Technology Laboratory (ETL) has been developing a hierarchy of models of the production of sea spray at high winds and the subsequent thermodynamic effects of the evaporation of spray on hurricane boundary layers. The three steps in this process are: 1) characterization of the size spectrum of droplets produced by the ocean as a function of the forcing (wind speed, stress, wave breaking, etc); 2) computation of the exchanges of heat and moisture between the droplets and an unperturbed near-surface layer structure; and, 3) accounting for the 'subgrid-scale' distortion of the standard surface layer T/RH structure by the droplets (a process referred to as 'feedback'). Our present sea spray source strength parameterization is derived from the Fairall-Banner physical sea spray model (which predicts the size spectrum of sea spray produced by the ocean in terms of wind speed, surface stress, and wave properties). The Fairall-Banner spectrum has been parameterized into a simple mass flux representation in terms of friction velocity. The unperturbed thermodynamic effects are based on integrals of the ratios of thermodynamic and suspension time constants following Andreas. Finally, the diagnostic feedback parameterization has been developed to characterize the way evaporating droplets of various sizes modify the stratification of the air near the surface, which in turn reduces further droplet evaporation but enhances sensible heat flux carried by the droplets. The present form of the parameterization has two tuning coefficients: one that scales the magnitude of the source strength and the other that affects the partitioning of enthalpy flux between sensible and latent heat.

Recently the parameterization was coded in F90 and implemented in the GFDL hurricane model and a version of Weather Research Forecast (WRF) model that runs at ETL. Preliminary tests on hurricanes Ivan and Isabel showed sensitivity to sea spray, but there are interdependencies with the non-droplet (direct) transfer specifications in the models. More testing is needed to understand these interdependencies (see: ftp://ftp.etl.noaa.gov/user/cfairall/onr_droplet/parameterization/)

B.5 EM-APEX Floats (James Girton, UW/APL)

A collaborative, ONR SBIR effort between the UW/APL and Webb Research Corporation (WRC) has developed an autonomous ocean profiling float that provides exceptional vertical and temporal resolution of velocity, temperature and salinity to depths of 2000 m for deployments of many years. Electrodes were added to the exterior of standard WRC APEX floats, and electronics were added inside. The electrode voltages result from the motion of seawater and the instrument through the Earth's magnetic field. Other systems included magnetic compass, tilt, CTD, GPS, and Iridium (that allow for sampling/mission changes).

Three EM-APEX (Electromagnetic Autonomous Profiling Explorer) floats were deployed from a C-130 aircraft ahead of Hurricane Frances as part of the ONR-sponsored CBLAST experiment. The floats profiled for 10 h from the surface to 200 m, then continued profiling and then between 35 m and 200 m at hourly intervals with excursions to 500 m every half inertial period (16 hr). The velocity computations were performed onboard and saved for later transmission. After five days, the floats surfaced and then transmitted the accumulated processed observations, then the floats profiled to 500 m every half inertial period until recovery early in October that was facilitated by GPS and Iridium positioning The resulting view of the evolution of upper-ocean momentum, shear, and stratification provides an important set of constraints for testing parameterizations of wind stress and ocean mixing in coupled ocean-atmosphere hurricane models. In addition, information on the direction and amplitude of the dominant surface waves can be extracted from high-frequency velocity measurements in the upper part of the profile.

B.6 ARGO Profiling Floats (Eric Terrill, SIO)

An autonomous profiling float now exists for observations of the upper ocean and air-sea interface during hurricanes. This observational tool was developed, tested, and, deployed as part of the ONR CBLAST experiments. The air-deployable profiler measures surface waves, wave breaking, wind-speed, and rainfall (via acoustic ambient noise inversions), Lagrangian currents, and the temperature and salinity structure of the upper ocean through rapid profiling of the upper 200 m of the ocean. The platform which hosts this unique set of underwater sensors is based upon a heavily modified SOLO float, which is similar to those now deployed in large numbers for the ARGO global climate monitoring system. The air deployment package is certified for usage from WC-130 aircraft.

During the 2004 season, we deployed nine units in the path of Hurricane Frances in collaboration with the AFRC 53rd WRS using NHC model track guidance for the airdrop locations and tasking from NHC. All nine units operated reliably through the course of the storm, with some units performing beyond expectation in their ability to transmit data during the winds exceeding 50 m s^{-1} using the ORBCOMM telemetry system. In addition to providing reliable data telemetry, the bidirectional communication system allows commands to be sent to the profiler to alter its mission after deployment. Unique to the platform is the development of a ‘hover’ mode that keeps the instrument at a nominal 30-50 m depth so that the air-sea interface can be probed with compact sonar for the direct measurement of surface waves.

Additional sensors onboard the instrument package include an acoustic system for processing ambient noise spectra in real time, a CTD package, a sonar altimeter for computing wave spectra, and a three-axis accelerometer. Two floats were equipped with a Aanderaa Optode for measuring dissolved oxygen. All sampling, power and communication with peripherals are done using a microcontroller that is independent of the vehicle control and telemetry system. The hurricane float missions included:

- Profile temperature and salinity to 200 m, which we anticipate is below the mixed layer
- Rise to a neutrally buoyant depth of O(30-50)m and enter a ‘hovering’ routine. While at this depth, the acoustic ambient noise field and surface wave field are sampled using the sonar altimeter, pressure sensor, and accelerometer.
- Profile to surface to obtain GPS position and transmit data using the ORBCOMM telemetry system.
- Repeat cycle every 4 hours for 180 dives.

For more information see http:// www.sdcoos.ucsd.edu/hurricanefloats.

Appendix A: Agenda for Air-Sea Interactions in Tropical Cyclones Workshop

Tuesday, May 24th

08:00 – 08:10 Stephen Lord and Naomi Surgi: Welcome, introduction and purpose of workshop
08:10 – 08:20 Nick Shay Motivation/Writing Charges

A. Forecaster Overviews:

08:20 – 08:50 Naomi Surgi: Operational Modeling at NCEP
08:50 – 09:20 Hendrik Tolman: Wave Modeling at NCEP
09:20 – 09:50 Carlos Lozano: Ocean Modeling at NCEP
09:50 – 10:20 BREAK
10:20 – 10:50 John Derber: Data Assimilation at NCEP
10:50 – 11:20 Isaac Ginis: Coupled Modeling at URI/NCEP
11:20 – 12:00 Discussion/Assignment of Break Out Groups

12:00 – 01:30 LUNCH/Informal Discussion

01:30 – 03:30 Break Out Groups 1/2
03:30 – 04:00 BREAK
04:00 – 05:30 Plenary Discussion/Chair Reports
05:30 Adjourn

Wednesday, May 25th

B. Research Overviews:

08:30 – 09:00 Nick Shay: Upper Ocean Observations
09:00 – 09:30 Gary Barnes: Atmospheric Boundary Layer Observations
09:30 – 10:00 Daniel Jacob: Ocean Modeling
10:00 – 10:30 BREAK
10:30 – 11:00 Chris Fairall: Sea Spray Parameterization Schemes
11:00 – 11:45 Discussion/Charge of the Break Out Groups
11:40 – 12:00 James Girton: EM-APEX Floats

12:00 – 01:30 LUNCH/Informal Discussion

01:30 – 01:50 Eric Terrill: ARGO Floats
01:50 – 03:30 Break Out Groups 1/2
03:30 – 03:45 BREAK
03:45 – 04:30 Plenary Discussion/Chair Reports
04:45 Adjourn

Appendix B: Breakout Group Questions:

Session 1:

Where is the air-sea community on observing and modeling the oceanic and coupled response to tropical cyclones? What is state of the art in areas of air-sea interaction/boundary layer processes and upper ocean physics? What promising technologies are on the horizon? Will they be available over the next 2 to 5 years?

How can we maximize recently acquired data sets such as ONR-CBLAST, NSF/ NOAA Isidore/Lili, HFP, MMS Georges data sets?

What are relevant time/space scales that models need to be resolved relative to intensity change? What is the impact of oceanic coupling on forecasting the atmospheric structure and intensity?

How do we improve initialization schemes? How important are positive feedback regimes such as the Gulf Stream, Loop Current on storm intensity and structure?

Can we use some of the work from GODAE for assimilation of satellite, drifter and float data?

What observations are needed to improve mixing parameterizations? What about wave coupling to the OML and ABL?

Session 2:

What is the appropriate mix of observations needed to improve the ocean and air-sea boundary layer processes in oceanic or coupled models?

What metric(s) are needed to be implemented for consistent assessment of model(s) performance? For example showing intensity changes from models is enough for a validation? How do we implement data and metrics in near-real time for forecasting needs?

What new real-time experimental plans need to be developed to support model forecasts? For example, sampling scenarios may differ over the Loop Current than the subtropical front in the North Atlantic.

Do we follow the life-cycle of one storm, or observe two storms under differing oceanic conditions each year? Will this be enough statistics to really improve the models?

How do we maximize use of GOOS float and ship-of-opportunity data? Will NDBC upgrades be useful? What about Coastal Ocean Observing Systems?

Do we rely on moored instrumentation? Or do we integrate time series from floats/drifters with snapshots from expendable sensors from aircraft?

Where do we see satellite remote sensing support going? What type of data will be useful in supporting experimental plans and data assimilation in models?

Appendix C: List of Participants/Breakout Groups (1/2, C:Chair)

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Appendix E: Data needs for the Air-Sea Component of Coupled Hurricane WRF

Necessary types and resolution of observations to define the coupled ocean-atmosphere problem for modeling:

1) Ocean structure and heat content

- Essential for verification (T, u, v, S)
- Radial and azimuthal resolution - critical between center and 200-250 km (24 h) ahead of storm
- Vertical resolution – mean values in the mixed layer critical – need to resolve mixed layer (2-4 m resolution)

2) Wind
- radial resolution most important – 0.5-1.0 km
- height resolution next most important – high resolution (100 m) in ABL, outflow, and to resolve eyewall

3) Moisture

- Vertical structure and latent heat fluxes
- Height resolution critical – high resolution (100 m) in ABL.
- Azimuthal resolution next most important
- Radial resolution – a function of Rmax.

4) Temperature profile

- Vertical structure and sensible heat fluxes
- Mean vertical profile, plus variation in radius
- Height resolution critical – high resolution (100 m) in ABL and near tropopause.
- Resolution a function of Rmax.

5) Ocean waves

- Essential for verification
- Azimuthal structure critical – resolve asymmetry in wave height and length – wave# 2
- Radial structure next critical – resolve radius of 8' and 12' seas - 20-50 km

Appendix E: Instrumentation needs for the Air-Sea Component of Coupled Hurricane WRF

1) Oceanic Structure

- Aircraft Expendables (AXCPs, AXCTDs, AXBTs): Weakness: limited time resolution
- Profiling Floats: Weakness: deployment into fronts
- Satellite IR. Weakness: no data in cloudy regions

- Satellite altimetery. Weakness: vertical projection in models
- Interferometric SAR: Weakness surface currents only
- HF radar networks: Weakness large gaps along the coastline
- Fixed/drifting buoys. Weakness limited spatial resolution (Cannot deploy in Loop Current, Gulf Stream)

2) Wind
- Airborne and ground based Doppler radars (limitation is winds only where it is raining, and poor vertical coverage near the surface because of ground clutter)
- Satellite Scatterometers/SAR and cloud drift winds (Weakness of scatterometer/SAR: only at the surface level. Weakness of cloud drift winds: coarse and uncertain vertical resolution
- Surface drifters: Weakness: one level
- Aircraft in-situ. Weakness: one level.
- Dropsondes. Weakness: limited spatial resolution
- Doppler LIDAR. Weakness: limitation to winds in non cloudy regions.
- SFMR. Weakness: only at surface.
- IWRAP?

3) Waves

- Radar altimetery (SRA):Weakness only Sweel Components
- Laser altimetery. Weakness limited to no cloud or precipitation
- Fixed/drifting buoys. Weakness limited spatial resolution
- Solo Floats
- SAR imaging

4) Moisture
- Dropsondes/Rawinsondes. Weakness: limited spatial resolution
- Microwave radiometric/interferometry. Weakness: limited vertical resolution
- Aircraft in-situ. Weakness: one level
- DIAL LIDAR (NASA LASE)

5) Temperature
- Dropsondes/Rawinsondes. Weakness: limited spatial resolution
- Radiometric/interferometry. Weakness: limited vertical resolution
- Aircraft in-situ. Weakness: one level

6) Rainfall

- Buoys/ground stations. Weakness one level and limited spatial coverage
- Radar/polarization diversity. Weakness limited vertical resolution, limited view near coastline, and calibration between radars
- SFMR rain. Weakness one level surface
- Satellite. Weakness: limited to cloud/no cloud
- Profilers and sub-millimeter radars

Appendix F: Breakout Group 1 Notes

Data Base for Observation-Model Comparisons: CBLAST and other data constitute a good basis for joint investigations by operational/OAR/University researchers: Need to create data base

What Ocean data are available?

  - 1988 - Hurricane Gilbert (Shay)
  - 2002 – AXCP, AXCTD, AXBT; Isidore and Lili (Shay and Uhlhorn)
  - 2003 – CBLAST 10 drifters/profilers Fabian
  - 2004 – CBLAST 40 drifter/profilers Francis and Jean
  - Collections of current profilers before/after storms – Steve Riser

- What Atm data are available?
  - HRD data base
  - Various NSF/CBLAST field programs
  - Coastal Radars
- What model outputs (initializations, NWP fields, HWIND)
- What satellite data
- Other data – waves, buoys,
- Metadata – descriptions, reports, papers, movies

Recommend allocating resources to set up infrastructure to create data base for existing data and facilitating rapid production of usable, quality controlled, standard products, integrated data for future hurricane program (HRD, FSU, NCAR-JOSS, NCDC?)

Maximize Usefulness of the data base

- Already discussed the need for model-usable data archive
- Questions about what data in which form
- Streamline future observation analysis
- Analysis of model outputs with data
- Comprehensive, easy to use

Observational Technologies Research and/or Transition to Operational

- Walsh's scanning radar wave measurement – 2D spectra available in realtime
- UAV – near surface fluxes/BL
- Airborne remote sensors for look-down near surface measurements (sea spray, wind profiles, breaking wave characteristics,)
- ARL batprobe for buoys (research)
- Ocean profilers

Our Big Three (four):

- Public data base for model studies to promote joint studies (see slides 1&2)
- Basic structure of near-surface BL in both ocean and atmosphere
  - Secondary Circulations
  - Mean profiles (u,T,q)
  - Upper boundary (fluxes, definition,..)
- Sea spray and enthalpy transfer coefficient U>30 m/s still a big question
- Ocean problems
  - Initialization
  - Mixing parameterizations

What observations to test coupled ocean-atmosphere models

- Before – snapshot synoptic field of ocean structure to 200 m …1000 m(u,v,T,S)
- During
  - Float array (u,v,T, S, P, waves, acoustics)
  - Airdrop profiler snapshots in storm
  - 2-D wave spectra surveys
  - Standard a/c everything package
- After – another snapshot along track
- Routine
  - NDBC enhancements (thermistors, stress,…)
  - ARGO, APEX floats; drifters
  - Coast Radar (HF, WSR-88D)
  - Gliders

What observations to advance coupled ocean-atmosphere physics and develop parameterizations: atmospheric

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

Appendix G: Breakout Group 2 Notes

- We are still a long way away from many aspects of the project (bulk transfer coefficient)
- Advancement of physics is a long term project.
- Just because we haven't made vast improvements, we are working toward a long-term goal
  - It may look like the GFDL model, but there are long term goals
- There is improved skill in the operational model

- Incremental upgrades => bigger impact on some things like track forecasting
- We can't degrade the track forecast in the HWRF or the project will not be accepted
- Same model is used for the East Pacific
    - Must also make sure that the East Pac forecast isn't degraded
- Started talking about what the actual weak points are of the project
    - Is it model components or the coupling?
        - Getting models to run together
        - Deciding what we are going to transfer between models
        - Physics problem & the coupling problem
- Increasing the levels from 42 to 64
    - This vertical upgrade should vastly improve the forecast
- Navy doesn't seem interested in the intensity of the storms
    - Intensity isn't correlated to the structure of the storm
- There is a need for scale dependent background
- Observational programs are very expensive
    - Must fully-utilize programs that we currently have
- There is difficulty in getting flux in high winds
- Hurricane Center needs buoy data
    - Wave part doesn't use data assimilation because of how quickly it moves away
- Is the ocean data coming in real-time? No- but it will be coming in soon
- Overcooling the upper ocean causing the air-sea interaction to die and the storm doesn't develop
- How should we deal with compensating errors?
    - We should try and put in the best science
- Need multiple parallel tracks
    - One for the best physics
    - Another one for research purposes and have the best science
    - Finally, one that does best in reality
- Until we have the observations of intensity, it's useless putting a forecast out.

Recommendations

- Series of sensitivity tests on coupled system when it becomes available
- Researchers need access to model output and vice-versa
- Maximize use of data sets
- Determine which data has value to assimilation, evaluation, validation

Where should we go in the next 5-10 years as far as modeling?

Modeling:

(1) Uncertainty in air-sea parameterizations, and depending on what you do, one can obtain any intensity that can be tuned to fit the best track data. From an observational perspective, we have to place error bounds on what are realistic values, but we still must address these parameterizations (e.g. c_h, c_d, sea spray).

(2) Timeline for HWRF is 2007 which sets the physics timeline. By this time next year, GFDL physics will be frozen, so advancements in physics will occur after this GFDL freezing. In other words, the physics of HWRF will be similar to GFDL.

(3) What observations will be useful for data assimilation? and for model evaluation (vice verification)?

Understanding:

(1) Constrained by resolution (i.e. computer resources) in terms of what we can explicitly resolve vs. what is parameterized.
(2) Can the intensity problem be addressed given the current resolution of the models? To some extent, but we must work within our computational constraints, so we should ask, "what can we address given a 9-km grid spacing?"

Timeline:

(1) If nothing else is done between now and 07 other than build the HWRF infrastructure and migrate the physics, it must be at least as skillful as GFDL to become operational.
(2) That is one of the issues. In HWRF development, comparing against the heavily tuned GFDL model so we might require a scientific side path to get the HWRF as good as GFDL.
(3) Purpose of everyone being here is that if all goes as planned with an operational HWRF in 07, then as long as we have been working on improvements all along, it will be possible to implement these improvements much faster (soon after initial operations).
(4) There should be opportunities for statistics and data to become available to researchers immediately so researchers can advise the forecasters in a timely manner

Weaknesses:

(1) Where are the biggest weaknesses? In the atmospheric, wave, or oceanic components? The first issue is getting all of the three components to work together correctly (technical issue). This is the current problem. Second issue: what parameters do you transfer between the different model components?
(2) For the atmospheric side, the parameterizations are the key issue. The other problem is the coupling problem between the various models.

Physics and Assimilation Issues:

(1) For ocean and wave model, are there similar parameterization problems such as incorporating Stokes drift, Langmuir Cells, wind-driven currents, and small-scale turbulence in wave model.
(2) Increase in vertical resolution from 45 to 64 levels, will affect physical parameterizations and in some cases not necessarily cost-effective for the gain in resolution (i.e. diminishing returns)
(3) From Navy's perspective, intensity problem should be separate from structure problem and may not be well correlated. That is, structure problem may be more amenable to advances in prediction than just intensity (max winds). This contrasts the NCEP view in that storm structure is well correlated to intensity.
(4) Underestimating the work required for good data assimilation into the models. What other than satellites would be helpful for modelers? AXBT's, altimeter data, floats,

aerosondes (UAV) for boundary measurements. These data should be able to be assimilated if it improves background states and intensity/structure predictability.

(5) Coastal Ocean Observing Systems are including high frequency Doppler current radars along the US coastline. Surface current measurements can help constrain the coastal ocean models (nudge towards reality) or Coastal Ocean Data Assimilation Experiments.

(6) Big issue: is the evaluation of model simulations in that it requires enough data coverage in space and time to account for model bias and uncertainty This is especially true when resolution decreases from submesoscale (<10 km) to the mesoscale (50 to 100 km). Observations must also capture this variability for a true comparison. We do not have enough of basic ocean data (T, S, u, v).

(7) Need differing types of observations (Eulerian and Lagrangian) to assess model performance in the global and coastal oceans. Most of these data used to be for local purposes, but now they are becoming widely available at various websites. Evaluation of model output must be done with data not assimilated into the model-parallel numerical experiments.

(8) Impact studies for each type of satellite data assimilated into models at NCEP-which satellite(s) are providing more bang for the buck.

(9) In only a few storms, we have model simulations with in situ data. Need to quantitatively assess cooling patterns (magnitude and spatial extent). However, cooling is sensitive to shear and stress-induced mixing parameterizations. Will we get better parameterizations or better assimilations from new observations?

Air-Sea Parameterizations:

(1) Observations suggest a leveling off of c_h and c_d some of which were based on similarity theory in the surface layer. Is this valid under high wind conditions? How do we parameterize the fluxes that can differ by factor of 2 depending on assumptions and surface layer thickness? Challenge is acquiring concurrent measurements in both fluids to address the problem.

(2) z_0 has wind speed and wave age dependency, but what about enthalpy flux above 30 m s^{-1} which may be constant. One possibility is to use ocean velocity measurements of mixed layer as evidence of momentum flux. Gridded ocean observations to help close the ocean mixed layer heat and salt budgets to estimate heat fluxes. Difficult to close the oceanic heat budget in high wind conditions, diagnostic model fields are beginning to converge to observed fields, but these simulations are sensitive to the imposed mixing scheme, initial ocean conditions and wind field. Still cannot get turbulent flux measurements down to 10-20 m… Note the same PBL and surface physics are in HWRF and GFDL. Current state is that GFDL is coupled to POM that will be coupled to HYCOM.

(3) There may be PBL issues related to resolution and at high-resolution, can get double-counting of eddies because of PBL parameterization being based on large eddy statistics. GFDL ocean and atmospheric data are archived, so these data can be validated w/ observations. Oceanographers can start looking at HYCOM output where observations show warmer mixed layers than predicted. This bias may be due to the fact that NRL initializes from biased climatology.

Model Initialization:

(1) Is there a sense in the model community of how much error there is in the initial ocean state prior to the storm? When you incorporate upper ocean observations that is much warmer than climo, it can make significant improvements in model simulations.
(2) What other kinds of observations are on the horizon? Drifters that can take temp (have thermistor chains) deployed by aircraft with an expected lifetime of months-year. Difficult to make good current and shear measurements from drifters.
(3) What spatial scale is required for moorings to make a significant improvement in models?. Assimilating data in wave models is pointless because there is no way of evaluating (eventually validating) the results. Need wave buoy data or SAR data from satellites etc. For the modeling effort, wave observations are not important, but it is vital for forecasters… it would be great to have the wave data from aircraft available in real time. SRA will eventually be transferred to NOAA with data link to NHC to acquire wave spctra from the time the aircraft leaves the coast until it gets back.
(4) Two issues with waves: if a sensor is deployed on a buoy/float in front of a hurricane, you will at best get a 1-D spectra because array is too small to get 2-D. Compact Doppler sonars can give you 2d, but it is difficult and you will need several buoys and floats to get the 2-D wave field. From data collection standpoint, it is much more feasible to collect wave data from aircraft ahead of storm (continuous measurements) than dropping buoys a few days in advance (risky because storm may avoid buoys).
(5) Oceanic mixing parameterizations: 6 diff mixing schemes yields 6 diff answers… can overcool upper ocean, etc…"coupled" model system is really just 3 models running together. It is important to test one or two at a time and conduct sensitivity studies to evaluate the output, rather than couple three differing models together with a detailed set of agreed upon metrics for rigorous evaluation.
(6) How should oceanic and atmospheric turbulence interact w/ the wave model where a vertical resolution of 1-2 m in the vertical is necessary in the surface mixed layer. SHOULD get down to this res. and do sensitivity experiments. In atmosphere, have sharp changes near surface, which is why surface layer fluxes are needed to rather resolve this. On the ocean side, when energy is transferred from atmos to ocean, see large diff when using 1 m resolution than when using 10 m resolution.

Coupling and Compensating Errors:

(1) What is the correct philosophical approach to dealing w/ compensating errors, esp. when dealing with coupled models. By including, e.g. wave model results in atmosphere model, could be including more realism.
(2) Need to put the best science first and foremost, but this may degrade the forecast, and forecasters won't deal with a degradation in track forecast. Have two parallel model experiments with a control data set with one model tuned by best forecasts and one with the "best" physics as we understand it. NCEP is always making tradeoffs…
(3) Parameterizations are not perfect… meant to work in specific ranges… the

"compensating errors" are what keep everything running. You run into all kinds of problems when you do "plug and play" physics because everything interacts nonlinearly. Sensitivity testing of different parameterization for numerical models require data (moored ADCPs from Ivan, airborne profiles from Isidore and Lili, float measurements in Frances, Georges mooring data) with concurrent atmospheric measurements. Thus we need to maximize use of the sparse (available data sets).

(4) Should feel comfortable enough with bulk transfer coefficients and sea spray to implement into model over the next two years. Still working on the vertical mixing scheme – only a few good data sets with current and shear to test schemes.

(5) Evaluating coupled models on storm "intensity" is not enough rather should also include size or storm structure in addition to max wind. Waves would be much worse in bigger storm… perhaps maximum wave height? At the present time it doesn't make sense to have wave metric because of lack of observations. Till 4 years ago, ATCF files just contained max winds, radius to max winds, pressure, and track location. Now includes max winds and location in each quadrant as well. If there is a strong signal, it should be model independent.

Recommendations:

- Series of sensitivity tests on coupled system when it becomes available
- Researchers need access to model output and vice-versa
- Maximize use of data sets
- Determine which data has value to assimilation, evaluation, validation

Experimentalists and theorists need to be aware of why or how model parameterizations perform under differing conditions. Forecasters have a responsibility to provide good forecasts, whereas experimentalists and theorists have a responsibility to acquiring high quality measurements and understanding them within the context of good science.

Note that we don't want duplication of effort… so communication between NCEP and other researchers are vital. Funding must be allocated for standardizing the observational and numerical data in a format that is easily and publicly accessible.