LANDFALLING TROPICAL CYCLONES: FORECAST PROBLEMS AND ASSOCIATED RESEARCH OPPORTUNITIES*

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with contribution from PDT-5#

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* Report of the Fifth Prospectus Development Team to the U.S. Weather Research Program

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Abstract

The Fifth Prospectus Development Team (PDT-5) of the U.S. Weather Research Program was charged to identify and delineate emerging research opportunities relevant to the prediction of local weather, flooding, and coastal ocean currents associated with landfalling U.S. hurricanes specifically, and tropical cyclones in general. Central to this theme are basic and applied research topics including: rapid intensity change; initialization of and parameterization in dynamical models; coupling of atmospheric and oceanic models; quantitative use of satellite information; and mobile observing strategies to acquire observations to evaluate and validate predictive models. To improve the necessary understanding of physical processes and provide the initial conditions for realistic predictions, a focused, comprehensive mobile observing system in a translating storm-coordinate system is required. Given the development of proven instrumentation and improvement of existing systems, three-dimensional atmospheric and oceanic data sets need to be acquired whenever major hurricanes threaten the United States.

The spatial context of these focused three-dimensional data sets over the storm scales is provided by satellites, aircraft, expendable probes released from aircraft, and coastal (both fixed and mobile), moored, and drifting surface platforms. To take full advantage of these new observations, techniques need to be developed to objectively analyze these observations, and initialize models aimed at improving prediction of hurricane track and intensity from global-scale to mesoscale dynamical models. Multi-nested models allow prediction of all scales from the global, which determine long-term hurricane motion, to the convective-scale, which affect intensity. Development of an integrated analysis and model forecast system optimizing the use of three-dimensional observations and providing the necessary forecast skill on all relevant spatial scales is required. Detailed diagnostic analyses of these data sets will lead to improved understanding of the physical processes of hurricane motion, intensity change, the atmospheric and oceanic boundary layers, and the air-sea coupling mechanisms. The ultimate aim of this effort is the construction of real-time analyses of storm surge, winds, and rain, prior to and during landfall, to improve warnings and provide local officials with the comprehensive information required for recovery efforts in the hardest hit areas as quickly as possible.

1. INTRODUCTION

The lead scientist of the U.S. Weather Research Program (USWRP) solicits advice and direction from the scientific community through prospectus development teams (PDT). These are small groups of scientists and technical experts who meet in a workshop format to discuss critical USWRP issues and report their findings and recommendations to the National Oceanic and Atmospheric Administration (NOAA) and the National Science Foundation (NSF).

Based on the recommendations from the first three PDT, the USWRP identified three research foci: (i) the importance and mix of observations; (ii) quantitative precipitation forecasting (QPF); and (iii) hurricane forecasts near landfall. The Fifth Prospectus Development Team (PDT-5) met from 30 April-2 May 1996 to identify and delineate emerging research opportunities relevant to the prediction of local weather, flooding, and ocean currents associated with landfalling U.S. hurricanes (specifically within 48-72 h), and tropical cyclones[1] (hereafter referred to as TC) in general. Central to this theme are fundamental and applied issues including: rapid intensity change; initialization of and parameterization in dynamical models; coupling of atmospheric and oceanic models; quantitative use of satellite information; and optimal adaptive observing strategies to validate predictive models. Specific charges include:

- Investigate and diagnose factors leading to rapid intensity changes of tropical systems, including interaction with upper atmospheric troughs and oceanic coupling, especially in the coastal zone;
- Develop improved methods for initializing dynamical hurricane models, including the use of radar reflectivity and Doppler velocity data, and improved model parameterizations for intensity forecasts;
- Conduct fundamental research and technique development to improve prediction of wind fields and precipitation patterns from landfalling systems and embedded convective storm hazards such as tornadoes;
- Exploit new and existing satellite information to diagnose storm intensity and short-term variability within cyclone structure; and
- Given operational dropwindsonde missions from the NOAA Gulfstream IVSP (G-IV) jet, further investigate optimal observing strategies for improved track forecasts within and beyond 48 hours and diagnose track forecast errors from dynamical models.

[1] tropical cyclone is a generic term for an intense warm-core cyclonic storm of tropical origin with highest sustained wind speeds >17 m s^{-1}. A tropical cyclone with highest sustained wind speeds between 17 and 32 m s^{-1} is referred to as a tropical storm, whereas, a tropical cyclone with highest sustained wind speeds $\geq$33 m s^{-1} is referred to as a hurricane or typhoon.

In our discussions, PDT-5 benefited from a continuing series of biennial workshops, begun in 1985, organized by the international TC research community that has examined the pertinent research and forecast problems related to TCs. These workshops have produced a series of concise reviews of the state of TC forecasting and research (ONR 1987; WMO, 1995). The U.S. TC research and forecast community has also organized an ad hoc committee to document our current forecast capabilities and to identify a research strategy to improve them (OFCM, 1997). Rather than duplicate these efforts, PDT-5 focused on the key TC forecast problems, and attendant research opportunities, relevant to landfalling storms along the U.S. coastline. In particular, PDT-5 focused its efforts on identifying new research opportunities related to emerging new technologies and techniques. Section 2 describes the problem, while section 3 details the critical science questions, and section 4 outlines the strategies and research opportunities.

2. THE PROBLEM

2.1 Background

The United States is more vulnerable to TCs now than at any time in its history. Millions of people live and vacation along the coastline and are exposed to the threat from TC wind, rain, storm surge, and severe weather. During this century, improved forecasts and warnings, better communications, and increased public awareness have reduced the loss of life associated with TCs. However, TC-related damage has increased dramatically. Coastal population growth in the U.S. of 4-5% per year (Sheets, 1990), is outpacing the historic 1-2% per year rate of improvement in official hurricane track predictions (McAdie and Lawrence, 1993). While specific track prediction models have indicated up to a 15% improvement over the past 2-3 years, very little skill has been shown in the prediction of intensity change (Elsberry et al, 1992). Adding to the public's vulnerability is a lack of skill in forecasting the intensity of wind, rain, storm surge and severe weather near landfall. For this reason, the average length of coastline warned per storm, about 570 km, has not changed much over the past decade. However, the average preparation costs have increased eight-fold in the past seven years from $50M per storm in 1989 to an estimated $300M per storm in 1996, or about $640K per mile of coastline warned (OFCM, 1997). Unless the rate of forecast improvements can be accelerated, the downward trend of TC casualties is not likely to continue, and the damage will continue to escalate.

The gains made over the last 40 years in our understanding and forecasting of TCs have depended critically on the mix of observations. New strides in our abilities have always paralleled the development of new research tools, from instrumented aircraft, to radar, to satellite. Each improvement in TC forecasting has been achieved by taking advantage of the available observations. The fact that a TC spends the majority of its life over the tropical ocean, where few data are available, has forced the community to pioneer mobile observing strategies in order to provide critical observations of the storm's location and strength. In addition, these techniques have evolved to include measurements of the upper ocean and atmosphere in the vicinity of the storm. Model parameterizations for atmospheric, oceanic, or coupled processes need high-quality, high-resolution observations. A synergism between observations and models is required to isolate the important physical processes.

Skillful forecasts of the TC surface wind fields, rainfall, and ensuing storm surge and severe weather depend on observations for a proper depiction of the initial state, and the ability of initialization schemes and forecast models to predict the future state of the atmosphere. Understanding and prediction of the surface wind and rainfall require knowledge of interactions throughout the depth of the troposphere over a broad spectrum of scales. While the partitioning of these processes that contribute to changes in the surface winds and rainfall remains uncertain, the combination of these processes strongly affects the changes. A major source of difficulty in past efforts to predict hurricane intensity, wind fields and storm surge at landfall has been the inability to measure the surface wind field directly and the inability to predict how it changes in response to external and internal forcing. Surface wind field parameters, such as the radius of maximum winds and the radii of hurricane force, 26 m s^{-1}, and 18 m s^{-1} force winds in each quadrant of the TC, must presently be estimated from a synthesis of scattered surface ship and/or buoy observations and aircraft measurements at 1.5 km to 3.0 km altitude (Powell et al, 1996 and Powell and Houston, 1996). This task is complicated by variations with height of the storms' structure, such as the change with height of storm-relative flow due to environmental wind shear and to the variable outward tilt of the wind maximum with height. Observations, theory and modeling need to be advanced to improve our understanding.

Forecasters from the three American TC forecast centers, The National Hurricane Center (NHC), the Central Pacific Hurricane Center (CPHC) and the Joint Typhoon Warning Center (JTWC), have recommended that one of their highest priorities in hurricane research is the improvement in hurricane wind field and intensity forecasting (OFCM, 1997). A major goal for hurricane forecasts is to mitigate the damage to the affected area caused by wind, rain, storm surge and severe weather within 48 h of landfall. The Federal Emergency Management Association (FEMA) requires coastal communities with limited escape routes to have completed preparation and evacuation before the arrival of gale force winds, typically 24 to 48 h before landfall. Considerable effort is required due to the lack of knowledge about fundamental mechanisms that inflict damage and impair our ability to provide timely warnings. Errors in wind, storm surge and rainfall forecasts have prevented the community from accurately defining the most vulnerable regions to expedite required preparations well in advance of the projected landfall. An example of this is described below using the Hurricane Opal case.

2.2 Hurricane Opal

During the evening of 3 October 1995, Hurricane Opal was located in the southern Gulf of Mexico, with a central pressure of about 950 hPa and peak winds of 50 m s^{-1} (for a summary of Hurricane Opal and its impacts see the NOAA Service Assessment Team Report (NOAA, 1996)). The storm had been slowly intensifying over the previous three days while drifting slowly over the Gulf of Campeche. Numerical guidance maintained that the storm would rapidly move north to northeastward, landfalling along the U.S. Gulf Coast. Given the small basin size of the Gulf of Mexico, Opal could strike anywhere along the coast within 24 h. Ambient sea surface temperature (SST) maps indicated the Gulf of Mexico was covered by water with temperatures >28°C. However, satellite altimeter observations also indicated that a sea surface height anomaly associated with a warm core eddy was located in the middle of the Gulf of Mexico along the forecast track. In addition, a strong upper-level trough was rapidly approaching the vicinity of the storm from the northwest, resulting in strong upper-level southwesterly winds over the storm. Figure 1 depicts the track of Hurricane Opal from 1-4 September 1995 relative to the locations of the oceanic warm feature and the upper-level trough.

During the middle of the night on 3 October, the storm started one of the most rapid deepening cycles that has ever been observed as it moved at 10 m s^{-1} toward the U.S. Gulf Coast. Within a 5 h period (from 0600-1100 UTC), U.S. Air Force Reserve (AFRES) reconnaissance aircraft measured a central pressure drop from 939 hPa to 916 hPa, while the estimated surface winds increased to nearly 70 m s^{-1}. Meanwhile, the flight meteorologist reported the eye contracted from a radius of 30 km to nearly 15 km. This rapid deepening presented the hurricane specialists with a major problem as the storm approached category 5 status within 12 h landfall of the U.S. coast without any means of alerting the public. Fortunately, over the subsequent 6 h the storm filled nearly as fast, reaching 940 hPa by landfall later that afternoon. The rapid filling phase was accompanied by decay of the eyewall and the formation of a secondary wind maximum and rainbands about 100 km from the storm center. However, as the storm made landfall, the storm surge and wave activity caused extensive damage along the coast (NOAA, 1996). Wind damage was confined to areas in the vicinity of the outer rainbands, while in the vicinity of the eyewall the wind damage was less than expected. Severe weather was reported along the Florida Panhandle and southern Alabama, extending as far east as the east coast of Florida, where tornadoes were reported in some of the outer rainbands. Rainfall, while heavy along the track of the eyewall and major rainbands as they moved inland, was less than forecast for such a strong storm (NOAA, 1996). By contrast, the storm surge seemed greater than anticipated for a 940 hPa storm, with the mean surge plus wave heights roughly twice that of the mean surge alone.

Based on this scenario, the mechanisms responsible for the storm track and speed changes remain unclear. More importantly, what were the relative roles played by the internal storm dynamics, upper-level trough and upper ocean on the significant intensity change that occurred over a 5 h period. Similarly, what processes governed Opal's equally rapid filling as it moved over water with shallower oceanic mixed layers, simultaneous with the arrival of the upper level trough? From the standpoint of forecasting the distributions of the surface wind, rainfall, storm surge and severe weather, why was the surge and the extent of the severe weather greater than expected, while the wind damage and rainfall was less than expected? It is questions such as these that PDT-5 chose to focus our attention on.

3. SCIENCE ISSUES

3.1 Research Objectives

In order to meet FEMA's evacuation requirements, forecasts of surface winds, rainfall, storm surge, and severe weather will depend on accurate intensity and track forecasts 48 h prior to landfall. Understanding and predicting intensity change and track requires knowledge of interactions throughout the depth of the troposphere over a broad spectrum of scales. Observations are sparse in upper troposphere, atmospheric boundary layer (ABL), and upper ocean, limiting knowledge of environmental interactions, angular momentum imports, boundary layer stress, and air-sea interactions. Moreover, SSTs remain an important, but incomplete measure of the ocean's influence on TC intensity change. Crucial unanswered questions concerning TC intensity change lie in the relative impact and interactions of three major components: (1) the structure of the upper ocean circulations that control the oceanic mixed layer (OML) heat content, (2) the storm's inner core dynamics, and (3) the structure of the synoptic-scale upper-tropospheric environment. A successful intensity forecast will require knowledge of the mechanisms that modulate TC intensity within the envelope defined by these three components.

Accurate forecasts of surface winds, rainfall, and ensuing storm surge and severe weather within 48 h of landfall also depend on accurate track forecasts. One of the more prominent efforts in TC research over the past two decades has been the study of storm motion or track under the US Navy Office of Naval Research (ONR) Tropical Cyclone initiatives (Elsberry, 1995). Operational TC track forecasting is a subjective process that combines conventional, satellite, and reconnaissance observations with input from objective prediction models. Factors such as enhancements of the observing network, development of new data assimilation techniques, and improvement of model resolution and physics contribute to increased model accuracy and reliability and produce improved operational forecasts. When a TC poses a potential landfall threat, one key element of the warning process is the forecaster's assessment of the likely track model errors. Therefore, as forecasters develop more confidence in their improved objective guidance, more accurate and/or precise warnings are possible.

Accurate modeling of TC motion requires accurate representation of interactions that occur throughout the depth of the troposphere on a variety of scales; this initial representation is determined through data assimilation that combines observations with short-term model forecasts. Observations are much less dense over the tropical and subtropical oceans than over North America. Since 1982, NOAA's Hurricane Research Division (HRD) has conducted a series of 18 experiments with research aircraft to enhance the upper-atmospheric observations in the vicinity of TCs over oceanic regions (Burpee et al, 1996). These experiments used an *adaptive sampling strategy* to deploy dropwindsondes, that measure vertical profiles of wind, temperature, and humidity between flight level and the sea surface, over a uniform grid surrounding the TC at radii <900 km from the center of the storm.

These experiments demonstrated that dropwindsondes are a cost-effective, high quality data source for improving initial wind and thermodynamic analyses of TCs and their near environment in oceanic areas with few in situ observations. The data produced statistically significant reductions in 12-60-h model track errors, relative to control runs. At these forecast intervals, which include the decision point for issuing of hurricane warnings, the average error reductions in the consensus forecasts from three dynamical models varied from 16% to 30%. The improvements are as large as the accumulated improvement in operational forecasts achieved over the 22-yr period from 1970 to 1991 (McAdie and Lawrence 1993) and represent a major breakthrough in TC forecasting capability.

Analyses and forecasts of the pattern, extent and intensity of damaging winds, rainfall and ensuing storm surge and severe weather at landfall require a combined observational and numerical approach encompassing three time periods: (1) pre-landfall (the period up to 48 h prior to landfall); (2) during landfall (±6 h around landfall); and (3) post landfall (>6 h after landfall). The long-term goal is to improve the near-surface wind field during these three periods. PDT-5 identified six tasks (the first four focused primarily on the landfall and post landfall periods, and the last two relating to all three periods) that will improve the analyses and forecasts of the pattern, extent and intensity of damaging winds and rainfall associated with landfalling TCs.

1) Improve the surface wind field representation in analyses, forecasts, warnings, and models through better knowledge of the surface wind field and the mechanisms that influence it.
2) Improve the analysis and forecasting of the surface wind field and oceanic response, including storm surge, in landfalling TCs by understanding relevant air-sea interaction processes.

3) Improve the analysis and forecasts of surface rainfall in forecasts, warnings, and models through better knowledge of surface rainfall and the mechanisms that generate it.
4) Improve severe weather forecasts and warnings in landfalling TCs through better observations of severe weather and the mesoscale environments supporting it.
5) Improve intensity forecasts up to 48 h in advance of landfall through improved observations of the internal storm dynamics, interactions of the storm with upper atmospheric and oceanic circulations, and modeling the physical processes.
6) Improve track forecasts up to 48 h in advance of landfall through improved observations of interactions of the storm with the surrounding atmospheric circulation, in particular upper atmospheric circulations, and modeling the physical processes.

All six of these objectives have strong ties between observations and model simulations. That is, a considerable fraction of the effort will require basic and applied research efforts in evaluating dynamical models with observations. Without this crucial step, the models will not be evaluated properly for their subsequent validation for use as operational tools by the forecasting community.

Several avenues of ongoing basic research utilize existing technological capabilities that could be improved in an integrated approach to examine these research issues (Appendix A). In particular, a number of new instruments and platforms have become available in the last few years that can be utilized to vastly improve our understanding of the mechanisms responsible for TC track, intensity change, and mitigation of damage caused by surge, wind, rainfall, and severe weather. In addition, there are a number of existing tools that can be utilized in new ways to improve our understanding.

3.2 Specific Research Questions

PDT-5 also came up with a list of specific research questions under each of the six objectives. They are enumerated below under each objective.

3.2.1 Improve the surface wind field representation in analyses, forecasts, warnings, and models

Knowledge of the surface wind field at landfall is important for improving not only wind warnings, but storm surge estimates and estimates of the rate of inland wind field decay. It has been generally agreed that changes in the wind field will be brought about by (1) changes in the large-scale environmental conditions, (2) changes in the underlying boundary and (3) evolving internal dynamics. *(landfall and post-landfall)*

(i) What processes regulate the pattern, extent, and intensity of damaging winds?

(ii) What are the characteristics of the surface wind fields at sea, at landfall, and in the transition from sea to land?

(iii) Given the lack of knowledge of topographical effects on winds, how does the inner core wind field evolve on multiple scales during and after landfall? These descriptions require, not only the characteristics of the wind field itself, but the tendency in the wind field, whether it is strengthening, weakening, broadening or shrinking.

(iv) The mechanics of TC spin-down after landfall are unknown. For example, are models of the surface layer wind changes valid in these high wind environments?

(v) What is the relative importance of roughness, cooling, friction, dry air, and time of day on decoupling vortex from surface layer?

(vi) Is there a difference between vortex spin down of a weak or strong TC? Does TC size affect the vortex spin down?

3.2.2 Improve the analysis and forecasting of the surface wind field and oceanic response, including storm surge, in landfalling TCs *(pre-landfall and landfall)*

(i) What is the spatial evolution of the surface waves, including the directional wave spectrum on OML depth variations, and their impact on the heat and momentum fluxes to the ABL during very high wind speeds? Surface waves inject turbulence into the OML and modulate the surface wind stress and alter the air-sea fluxes.

(ii) Why is there such disparity between various storm surge predictions and the available sea level information? The accuracy of storm surge forecasts depends critically on wind forecasts, yet analyzed wind fields are not being used in these forecasts.

(iii) Two-dimensional current fields from storm surge models need to be validated with available current data. Do storm surge models produce representative momentum fields?

(iv) Complex interactions occur between surge and wave fields and the TC wind fields. How do the surface waves interact with the coastal currents and tides to produce observed sea level changes?

(v) Do the evolving surface waves act as turbulent gusts of energy superposed on the storm surge in much the same way turbulent wind gusts are embedded within the TC wind field?

3.2.3 Develop improved analysis and forecasts of surface rainfall *(landfall and post-landfall)*

(i) What processes cause the pattern, extent, and intensity of rainfall including when remnants of the TC interact with extratropical systems and topography well after landfall?

(ii) What are the characteristics of the rain fields at sea, at landfall, and in the transition from sea to land?

(iii) Given the lack of knowledge of topographical effects on rainfall, how do the inner core and rainband precipitation fields evolve on multiple scales during and after landfall?

(iv) How can the new satellite products (infrared, visible, water vapor (WV), Special Sensor Microwave/Imager (SSM/I), Altimetry, Scatterometry, etc.) be used to better estimate and forecast storm rainfall?

(vi) How can the new WSR-88D radar products be used to better understand and forecast storm rainfall?

3.2.4 Develop improved severe weather forecasts and warnings in landfalling TCs *(landfall and post-landfall)*

Damage from severe weather is not confined to the region surrounding the eyewall. It often extends to the periphery of the storm. Tornado formation from landfalling storms needs to be better understood to refine the forecasts.

(i) Are there different mechanisms producing severe weather in the vicinity of the eyewall and in the outer rainbands?

(ii) What flow structures are responsible for the most severe damage: tornadoes, downbursts, or straight-line winds organized by ABL circulations? How often do these phenomena occur within the TC core, and in the outer rainbands?

(iii) What are the characteristics of tornadoes associated with TCs? Are they similar or different to those seen in the mid-west U.S.?

(iv) What is the relationship between tornado production/organization and the kinematic and thermodynamic structure of the TC and its environment? For tornado production, what is the relative importance of vertical shear associated with surface drag, ABL cooling, or interaction with a baroclinic environment?

(v) What is the most meaningful measure of thermal stability in the core of TCs? What is the variability of convective available potential energy within and between the rainbands of TCs?

3.2.5 Improve intensity forecasts up to 48 h in advance of landfall *(pre-landfall, landfall and post-landfall)*

Accurate forecasts of surface winds, rainfall, storm surge and severe weather within 48 h of landfall depend on accurate intensity forecasts. However, observations are sparse in the upper troposphere, ABL, and OML, limiting our knowledge of environmental interactions, angular momentum imports, ABL stress, and air-sea interactions. To accurately predict intensity the relative role or influence of three effects are required: (1) internal storm dynamics; (2) interactions with upper atmospheric circulations; and (3) interactions with the underlying ocean circulations. For progress to be made on intensity predictions over the next decade, the partitioning of the uncertainty between these three effects on TC intensity has to be addressed from both observational and numerical perspectives. PDT-5 came up with specific science questions for each of the three effects:

a) *Internal storm dynamics*;

(i) What role does the wave number one asymmetry play in the evolution of the vortex core?

(ii) Many aspects of rainband formation, dynamics, and interaction with the symmetric vortex are still unresolved. What mechanisms lead to the outward and inward propagating rainbands? How do the internal rainband circulations feedback on the primary vortex?

(iii) Determine what mechanisms lead to convective ring formation. Three-dimensional numerical simulations of the TC evolution have not been able to reproduce realistic rainbands, particularly convective rings. Is the model resolution too coarse? Is the convective parameterization adequate? Are all of the relevant physical mechanisms simulated?

(iv) Are eye-wall cycles incidental or an essential part of the interaction of the vortex with its surroundings and the subsequent intensity change. Is there a natural time-scale in the eye-wall cycles that significantly alters the intensity of the TC?

(v) Provide a better representation of the inner core in operational models.

b) *Upper atmospheric circulations*; and

(i) Interactions between the storm and the upper atmospheric circulations are poorly understood. What is the distinction between a trough that leads to a storm's intensification upon interaction with the storm (good trough) and one that leads to a storm's decay (bad trough)? Both theoretical and numerical modeling research of this phenomenon have been constrained by the lack of data throughout the troposphere between the outer edge of aircraft reconnaissance data (150 km radius) and 400 km radius where these interactions occur.

(ii) Sudden deepening during interaction of the TC with a upper-tropospheric circulation associated with upper-tropospheric potential vorticity (PV) anomalies (e.g., Molinari et al, 1995) . Since these interactions occur ~35% of the time, do they represent the most common upper boundary interaction for TCs?

(iii) Larger scale dynamics in the case studies to date are not fully understood. A balanced vortex approach averages out the azimuthal dimension and frames the problem as one of forcing and response. Does a complete understanding require a three-dimensional, time-dependent description of the two interacting features?

c) *Upper ocean circulations*

(i) What is the upper-ocean heat potential associated with OML depth variations in the vicinity of basic state currents? Is it a better measure of the ocean heat content than SST alone?

(ii) What are the horizontal advective tendencies and transports by basic state currents? How do these horizontal temperature gradients alter the oceanic response and the air-sea fluxes that feed the TC?

(iii) What are the relative roles of shear-induced turbulence across the entrainment zone (at the OML base) and stress-induced turbulent mixing due to the variability in the near-surface wind field on the OML heat content?

(iv) What is the spatial variability in the air-sea fluxes within and surrounding the eye, and their relationship to the upper ocean processes?

(v) What is the spatially-evolving surface wave field and what relationship does it have to the OML depth variations and its effect on the heat and momentum fluxes in the ABL?

(vi) Air-sea flux variations and the behavior of the bulk aerodynamic coefficients indicate considerable uncertainty at very high wind speeds. Given that many of these relationships were determined from ABL experiments over land, is it realistic to use them in coupling the two fluids during very strong winds when the ABL is already destabilized?

3.2.6 Develop improved track forecasts up to 48 h in advance of landfall *(pre-landfall, landfall and post-landfall)*

Accurate forecasts of surface winds, rainfall, storm surge and severe weather within 48 h of landfall depend on accurate track forecasts 48 h prior to landfall. Significant advances in TC track prediction have been made over the last 10 years, yet the track issue continues to be problematic to forecasters particularly near landfall.

(i) Lack of mid- to upper-level atmospheric structure data in tropics has hampered the assessment of the importance of a spectrum of horizontal scales affecting storm motion and physical processes such as convection and air-sea interaction. What new data are required to improve model and operational forecasts?

(ii) What is the role of baroclinic processes on track changes and how do storm interactions with upper-tropospheric circulation anomalies affect track and intensity change? Improved understanding is needed of the physical processes affecting track through a combination of mobile observing studies using ensemble model and operational model output.

(iii) What effects does landfall (changing surface influences) have on TC tracks?

(iv) Can our increased understanding of the principles of cyclone movement be converted into improved forecasts near landfall? Theoretical studies need to be used to provide conceptual models for forecasters to better understand when and why TC motion deviates from the basic steering concept.

(v) Can ensemble forecast techniques be used to improve our TC track forecasts and improve our knowledge of the prediction uncertainty? Studies need to be conducted to test the ensemble approach in simple as well as complex TC track forecast models.

4. STRATEGY AND RECOMMENDATIONS

4.1 Linkages to other USWRP foci

The USWRP landfalling hurricane foci contain aspects of the other two foci. The gains made over the last 40 years in our understanding and forecasting of TCs have depended critically on the mix of observations. New strides in our abilities have always paralleled the development of new research tools, from instrumented aircraft, to radar, to satellite. Each improvement in TC forecasting has been achieved by taking advantage of the available observations. The fact that a TC spends the majority of its life over the tropical ocean, where there is very little data available, has forced the community to pioneer *adaptive observing strategies* to provide critical observations of the storm's location and strength. These techniques have evolved over the last 40 years to include observations of the upper ocean and atmosphere in the vicinity of the storm, as well as, its location and strength.

Hurricanes also pose a major precipitation forecast problem. Estimates of rainfall based on radar data, satellite imagery, and numerical models offer promising avenues for improvement, however, the prediction of TC rainfall beyond 3 h has little skill for all but the most general indications. The primary convective and stratiform precipitation mechanisms are active in TCs. The location of mesoscale disturbances, which depend on smaller circulations than the available observations can detect, determine the distribution of precipitation. In short the TC provides a perfect laboratory for testing many of the QPF techniques.

PDT-5 feels strongly that a concerted effort by USWRP to address the scientific questions related to landfalling TCs would go a long way toward improved understanding of the QPF problems and a better use of the mix of observations. With that in mind, PDT-5 outlined an observational, analysis and modeling strategy to address these important questions.

4.2 Observational Strategy

PDT-5 proposes a strategy to develop a mobile observing system that can be positioned in front of any landfalling TC within 24 h of landfall. The observing system is based upon the NOAA (WP-3D and G-IV), NASA, and USAF Reserve (AFRES) aircraft (and airborne expendables), portable profilers, Doppler radars, and a surface mesonet. The observational strategies will require careful planning, organization, and coordination with built-in flexibility to allow adjustments to quickly evolving and poorly predicted storm conditions and availability of observing platforms. Unlike typical field deployments where a number of observing systems are deployed for intensive observations during a 3-4 week period within a relatively limited geographical area, this effort will require intensive observations for one- to three-day periods as a TC approaches anywhere along the Gulf of Mexico or east coast of the US during the six months of hurricane season. The proposed plan develops the observing system over the next five years, testing different components through trial deployments during the annual hurricane field program run by NOAA's HRD, leveraging upon NOAA's considerable commitment to ongoing TC research. Each year as many components of the observing system as possible would be tested in any potential landfalling storms along the US East or Gulf Coast.

A key component of such an observation strategy is to make full use of operational observing systems such as rawinsondes, Automated Surface Observing System (ASOS), Coastal-Marine Automated Network (C-MAN), moored buoys, WSR-88Ds, and satellites and augment these observations with a research-quality mobile observing system. This mobile observing system would take advantage of existing and newly developed airborne and surface-based observing capabilities. Improvements to in-situ and remote sensing technology provide a unique opportunity to sample the destructive winds in a TC offshore before landfall, and over land during landfall using a mobile observing system.

Offshore components will include airborne remote sensors (scatterometers and radiometers), and expendables (Global Positioning System (GPS) dropsondes, drifting buoys, bathythermographs, and current probes) to estimate near-surface wind fields, changes in the upper-ocean currents and waves, and air-sea fluxes. The remote sensors accurately measure the location and magnitude of the maximum surface winds without the uncertainty of adjusting flight-level winds to the surface using an ABL model. Doppler radars onboard the WP-3D aircraft provide wind estimates at altitudes as low as 0.5-1.0 km. Winds at these levels are critical because they often reflect the level of maximum winds and enable adjustment to the surface with fewer errors than flight-level data. Newly developed GPS dropsondes, deployed from aircraft (NOAA, NASA, or AFRES) offshore provide high vertical resolution wind and thermodynamic profiles from flight level down through the level of maximum winds to the surface, linking all the observations into a vertical frame of reference. New mini-drifting buoys, provided by the NOAA National Data Buoy Center (NDBC) can be deployed from aircraft offshore in advance of a threatening storm and transmit surface wind and thermodynamic data, as well as SST.

On-shore components will need to use a variety of mobile and transportable observing systems equipped with Doppler radars, ABL wind profilers, and conventional meteorological instruments to measure surface winds, precipitation, temperature, humidity, low-altitude wind, temperature and moisture profiles, and two-dimensional and three-dimensional meso- to convective-scale wind structures within rainbands and other convective features of the storm. Remote sensing systems on the NOAA WP-3D and NASA aircraft will also be used over land whenever possible to map storm structure and evolution. Since it may be difficult to have all observing systems available during the entire hurricane season, the exact suite of instruments may vary from storm to storm.

The observing strategies will focus on the three major phases of the storm evolution near landfall outlined in the previous section: pre-landfall (t=-48 to -6 h), landfall (t=±6 h of landfall), and after landfall (t>6 h). Detailed plans will have to be developed to coordinate the deployment of the platforms involved in each of these different phases. As a storm approaches the US specific plans will be selected and fine-tuned in accord with the predicted storm conditions and the observing platforms available. The measurement and deployment strategies will be evaluated and modified as experience is gained and as different observing systems become available for deployment.

The coordination of the observational components can be made through NOAA's HRD as part of, or an augmentation to, their annual field program to study landfalling TCs. Key mobile land-based systems may be deployed to pre-selected sites along the US coast. These sites need to be identified and surveyed before any deployments are made. National Weather Service Meteorologists in Charge (MIC) and Science Operations Officers (SOO) will be briefed about the observational objectives and consulted during the site survey and selection process. Although a detailed list of criteria for site selection will be developed, the WSR-88D coverage at the sites will be given primary consideration since one important objective is to develop techniques for making full use of the observing systems developed under the National Weather Service modernization. Thus it is important that these observing systems be fully integrated into the experiment design.

4.3 Analysis And Modeling Strategy

Development of an integrated analysis and model forecast system optimizing the use of observations and providing the necessary forecast skill on all relevant spatial scales is required. The proposed plan develops an improved analysis and modeling system over the next five years, testing different components through trial data sets collected during the enhanced observing program, leveraging upon NOAA's and the Navy's considerable commitment to improved data assimilation, analysis, and modeling. To take full advantage of these new observations, techniques need to be developed to objectively analyze these observations, and initialize models aimed at improving prediction of TC track and intensity from global-scale and mesoscale dynamical models. Multi-nested models allow prediction of all scales from the global, which determine long-term TC motion, to the convective-scale, which affect intensity. Coupled atmospheric and oceanographic models can be used to improve the understanding of the role of the OML and ABL on intensity changes over short-time intervals. Considerable progress has been made in oceanic and atmospheric models, however detailed evaluation and validation using observations as a guide remains a key part of the simulated response and the coupled processes.

A key goal of the analysis and modeling strategy is to improve the surface wind field representation in forecasts and warnings . Most numerical models are capable of using objective gridded analysis from global down to regional resolution. Present TC models typically use a global analysis and modify the near storm region by using a "bogus vortex" based on limited observational data such as maximum winds, radius of maximum and gale force winds, etc. This has the advantage of prescribing a "realistic" storm into an objective analysis where data scarcity may lead to an otherwise poorly resolved storm. Other models usually do not apply this technique especially near landfall. This will lead to additional disparity between various model initial conditions and must be factored into forecast decisions.

Another goal of the modeling strategy is to improve the parameterization of sub-grid scale processes in the numerical models. The ABL and OML and associated surface fluxes are critical to the very existence of TCs, but surprisingly little is known about their behavior in high wind, fetch-limited wave conditions. Models depend on parameterization of these sub-grid scale processes. By model standards TC landfall takes place rather rapidly (~24 h) over which the wind decrease is primary attributable to the reduction of these fluxes and an increase in surface roughness. Other factors that significantly affect this phenomenon are coastal and topographical interactions, and interaction of the storm with mid-latitude baroclinic systems.

Finally, our ability to forecast precipitation and severe weather in TCs needs to be vastly improved. Besides storm surge and high wind, heavy precipitation is an additional landfall phenomenon which has serious flooding consequences that often penetrate several miles inland. Prediction of rainfall is often a more serious challenge for dynamical models than that of traditional variables of wind and temperature. Severe weather often breaks out during TC landfall. This includes mesovortices and downbursts and tornadoes that may occur near the coast or well inland. This is a major challenge for regional and mesoscale dynamic model prediction.

Detailed diagnostic analyses of these data sets will lead to improved understanding of the physical processes of TC motion, intensity change, the ABL, and air-sea coupling. Ultimately, the aim is on development of real-time analyses of storm surge, winds, and rain, before and during landfall, to improve warnings and provide local officials with the information needed to focus recovery efforts in the hardest hit areas as quickly as possible.

4.4 Specific Recommendations

In parallel with the overall observational and analysis and modeling strategies, PDT-5 compiled a list of specific recommendations for research opportunities under USWRP. These are listed below by the six topic areas outlined in section 3.

4.4.1 Improve the surface wind field representation in analyses, forecasts, warnings, and models

(i) Determine flow structures responsible for most severe damage using aircraft, WSR-88D, ASOS, mobile radar, and profilers in an adaptive observing strategies to quantify the multiple scales during and after landfall. Temperature and moisture data aloft are required from soundings and Radio Acoustic Sounding System (RASS) as mobile sensors will provide improved surface fields.

(ii) Combine the WP-3D, GPS dropsondes, Stepped Frequency Microwave Radiometer (SFMR)/C-Band Scatterometer (C-SCAT) with Airborne eXpendable Current Profilers (AXCP) and Airborne eXpendable Bathythermographs (AXBT) in an adaptive observing system over the water, to acquire complete near-surface wind data sets on the relevant physical mechanisms in establishing the boundary conditions prior to landfall. The feedback between OML and ABL, and transition of ABL over land is relatively unknown, which is a critical aspect in the air-sea-land interactions.

(iii) Assess the role of coastal and inland topography on the near-surface wind fields by developing appropriate models by combining observations with GFDL, ETA, or NOGAPS model guidance, which suggest winds at top of ABL decay more slowly than at surface. Since coastal effects depend on whether storm is intensifying or filling, the range of vertical wind and gust profiles for onshore and offshore flows for differing ABL stratifications in filling and intensifying TCs has to be determined. The understanding of wind gustiness in the eyewall at landfall including the presence of mesovorticies may be improved using rapid scan 1-min interval GOES satellite and WSR-88D observations.

4.4.2 Improve the analysis and forecasting of the surface wind field and oceanic response, including storm surge, in landfalling TCs

(i) Acquire best available wind field and storm track to force storm surge models. Key parameters are wind speed, radius of maximum winds, detailed mesoscale wind distribution, and any knowledge of the storm structure near landfall. Sensitivity studies are needed to assess the benefits of using surface wind analysis or GFDL, ETA, and/or NOGAPS model output for storm-surge modeling.

(ii) Incorporate tides and surface waves into storm surge models and verify the sea level predictions as well as the currents, tides and surface wave observations in fully integrated storm surge models. Interactions between tides, surface waves and storm surge are relatively unknown and are needed to produce an accurate forecast of total water level particularly in regimes where the tidal range is large. Post-storm verification of storm surge forecast with observed heights, waves and currents is critical to improve model physics and numerical approaches.

(iii) Include free surface, three-dimensional ocean circulation model with proper initialization and bottom relief to account for baroclinity as Florida Current and Gulf Stream impinges over shelf break. Numerical models capable of handling baroclinic regimes with a free surface are needed to understand baroclinic and barotropic interactions in the coastal ocean, and their relationship to storm surge near landfall.

4.4.3 Develop improved estimates of surface rainfall in TC forecasts, warnings, and models

(i) Improve utilization of WSR-88D, SSM/I and other satellite data products to understand and forecast TC rainfall by developing specific rainfall algorithms, reflectivity-rainfall relations, or techniques.

(ii) Determine the physical mechanisms that alter rain-cell life cycles at landfall and improve the rainfall estimation techniques, such as expanding the utility of the stratiform/convective classification of precipitation.

(iii) Develop QPF tools for landfalling TCs and determine the critical parameters to document the skill of the GFDL, ETA, and NOGAPS models. Improve the model physics and resolution to accommodate intense rainfall events after landfall as TC remnants interact with extratropical systems and topography. Forecasting techniques for inland TCs must be developed as an enhancement to those for daily precipitation forecasting during summer season, particularly with respect to asymmetries; precipitation in the eyewall and outer bands; and moisture transport to outer peripheries of the storm.

4.4.4 Develop improved severe weather forecasts and warnings in landfalling TCs

(i) Utilize high-resolution aircraft, WSR-88Ds, mobile Doppler radars (DOW), profilers (mobile and fixed) and rawinsonde (standard and mobile) data to describe thermodynamic and kinematic environment supporting the severe storms and discriminate between supercell and non-supercell storm potential. In addition to testing and evaluating new algorithms, these data are needed to describe the structure of shear lines within rainbands prior to, during, and subsequent to landfall, and how these structures compare to those from other types of boundaries. Better understanding of the evolution of rainbands following landfall may improve predictability of post-landfall severe weather.

(ii) Increase understanding of critical parameters leading to tornado genesis and mesovortices in landfalling storms, and determine to what extent severe weather is present in TCs at sea.

(iii) Maximize progress on the severe weather forecast problem by considering the impact of TC-external influences such as upper tropospheric circulations (PV anomalies), or dry-air intrusions, on the TC's evolving thermodynamic and kinematic fields.

(iv) Observational studies of severe weather in TCs using WSR-88D data require further algorithm development and refinement to allow for more complete diagnostic analyses.

(v) Pursue studies of the relation between TC severe weather and National Lightning Detection Network (NLDN) data patterns.

4.4.5 Improve intensity forecasts up to 48 h in advance of TC landfall

a) *Inner Core Dynamics*

(i) In order to isolate physical processes, acquire more complete data sets using mobile observing strategies combining the WP-3D, GPS dropsondes, with AXCPs and AXBTs over water, and WSR-88D, C-MAN, ASOS and DOW over land.

(ii) Improve understanding of asymmetric structure of TC wind and surface fields to improve knowledge of mesoscale structure changes within intensifying TCs. In particular, examine the relative importance of wave number 1 and 2 asymmetries to TC intensity change and their interactions with the surrounding environmental flow.

(iii) Develop high-resolution three-dimensional models to investigate the relative importance of dynamic instabilities, microphysical processes, and interaction with upper-level atmospheric circulations in intensity change. Examine the mechanisms leading to the formation of secondary eyewalls, which has yet to be accurately simulated by the models. Understand the role of microphysics on the structural evolution by combining microphysical measurements with *in situ* electric field, radar, and NLDN observations.

b) *Upper Tropospheric Circulations*

(i) Combine observations from special rawinsondes, GPS dropsondes, and flight-level data from the G-IV acquired over a large area surrounding the TC with data fields derived from GOES WV imagery to describe the thermodynamic, and the kinematic fields to compute angular momentum transports, shear, and PV. These data should provide a thorough description of the immediate TC environment, and vastly improve the description of the TC.

(ii) Develop and initialize theoretical and numerical models for TC-trough interactions with observations from a variety of TCs to simulate the observed evolution of the interacting systems, and verify the approach using the operational GFDL, ETA, and NOGAPS models. Determine through selective data assimilation which new observations the simulations are most sensitive to, and use this information to prioritize future data acquisition.

c) *Upper Ocean Circulation Anomalies*

(i) Develop a more complete measure of the oceanic heat potential to support TC intensity changes using The Ocean toPography EXperiment (TOPEX) altimeter and Advanced Very High Resolution Radiometer (AVHRR) data validated by three-dimensional observations from AXCPs and AXBTs in focused, movable experiments over warm core eddies, the Loop Current, the Gulf Stream. *In situ* measurements are required to relate the OML, ABL, and sea surface processes before, during, and after the passage of TCs to the near-surface wind field and intensity change using a combination of expendable profilers and drifters, remote-sensors such as the SFMR and C-SCAT, Scanning Radar Altimeter (SRA), and the radome gust probe.

(ii) Develop objective methods to analyze three-dimensional structure observations to assess the relative roles of horizontal advection and vertical mixing processes that cool and deepen the OML, and compare the fields from numerical model simulations. Improve parameterizations with respect to coupled air-sea interactions such as the bulk aerodynamic coefficients related to the latent and sensible heat and momentum fluxes, which are crucial in the coupled simulations and feedback between the OML and sea surface to the ABL.

(iii) Verify model simulation from oceanic and coupled models in an effort to isolate physical processes from operational intensity forecast models and coupled atmosphere-ocean models. Evaluate and validate mesoscale coupled atmosphere-ocean models using three-dimensional data and assimilation of satellite data. Incorporate a third generation wave model (e.g., WAve Model Development and Implementation Group (WAMDI), 1988) in mesoscale coupled models to examine role of surface waves on OML and ABL budgets over warm ocean features and continental shelf.

4.4.6 Develop improved track forecasts up to 48 h in advance of TC landfall

(i) Integrate new sampling strategies for dropsondes from coordinated G-IV and WP-3D flights, satellite, NLDN and WSR-88D into track model forecasts to understand the role of upper tropospheric circulations (PV anomalies) on the track. Data sets can be used to better define the wave-number 1 asymmetries and improve our understanding of the interaction of the vortex with the surrounding flow.

(ii) Improve track forecasts by continuing track research especially in areas of ensemble, extended range, extratropical influence/transition forecasts, and the use of adaptive observational strategies to optimally utilize the data. Foster new approaches in forecasting track and data assimilation of G-IV, GPS dropsondes, WV wind data into the GFDL, ETA, NOGAPS, and other operational models to improve track forecasts.

(iii) Expand the role of GFDL, ETA, and NOGAPS output to examine PV anomalies, rainfall, ABL processes and their role or dependence on track forecasts. Emphasis on how fields produced by these models, besides track, can be used for verification when used with observations. The use of the WWW is needed to facilitate rapid transfer of information to the research and forecasting communities.

(iv) Develop WSR-88D analysis techniques for tracking TCs at NHC, CPHC and JTWC that can be applied to the network of radars rather than to individual sites. The current philosophy for use of the WSR-88D focuses on each site's ability to improve local forecasts. A network-oriented approach is needed for the TC problem; one that benefits each hurricane center's forecast capability.

5. SUMMARY

The research and forecasting communities have arrived at a critical juncture. The National Weather Surface has nearly completed its modernization, installing new Doppler radars, automatic surface stations, the next-generation weather satellites, and new computer systems. Emerging technologies have matured to a state where observations and models should be integrated into a consistent framework to improve forecasts and analyses of surface winds, rainfall, and ensuing storm surge and severe weather within 48 h of landfall. A recurrent theme in the PDT-5 deliberations has been a synergism between observations and models in isolating physical processes. High-quality, high-resolution observations of atmospheric and oceanic fields are crucial to evaluate and eventually validate models of the atmospheric, oceanic, and coupled processes. Integration of various components of the hurricane forecast problem (e.g., improved physical understanding of the processes that cause damage and track and intensity changes) has the best chance for success.

To acquire the necessary understanding and provide the initial conditions for improved prediction, a focused, comprehensive observing system in a translating storm-coordinate system is required. Combining proven instrumentation with a number of new instruments and platforms that have become available in the last few years (Appendix A), three-dimensional wind and thermodynamic data sets can be obtained whenever major TCs threaten the United States. Satellites, aircraft, expendable probes released from aircraft, and coastal, moored, and drifting surface platforms are needed to estimate the upper-ocean temperatures and currents, air-sea interactions, the distribution of storm surge, ABL winds, rainfall, and potential damage. In the TC core, airborne Doppler radar, supplemented by a suite of other instruments, measures tropospheric winds including critical areas of the ABL and outflow region. Microwave systems estimate surface winds, ocean waves, and storm surge. On the TC periphery, dropsondes released from turboprop and jet aircraft map the atmospheric temperature, humidity, and wind structure. Satellites acquire both storm-scale and surrounding environmental data.

To take full advantage of these new observations, techniques need to be developed to objectively analyze these observations, and initialize models aimed at improving prediction of TC track and intensity from global-scale and mesoscale dynamical models. Multi-nested models allow prediction of all scales from the global, which determine long-term TC motion, to the convective-scale, which affect intensity. Development of an integrated analysis and model forecast system optimizing the use of observations and providing the necessary forecast skill on all relevant spatial scales is required. Detailed diagnostic analyses of these data sets will lead to improved understanding of the physical processes of TC motion, intensity change, the ABL, and air-sea coupling. Ultimately, the aim is on development of real-time analyses of surface winds, rain, and ensuing storm surge and severe weather before and during landfall, to improve warnings and provide local officials with the information needed to focus recovery efforts in the hardest hit areas as quickly as possible.

The U.S. Weather Research Program (USWRP) (Emanuel et al, 1995) and World Weather Research Program (WWRP) have identified landfalling TCs as a major focus of their research programs. It is in the national interest to mitigate damage that occurs after TCs make landfall. Over the next decade, these issues will have a significant impact on building codes, construction technology, preparedness lead times, and evacuation procedures, all aimed at saving lives and minimizing property damage. Even if the improvement in intensity predictions is only a few percent per year, the benefit to cost ratio is high, leading to an improvement over the present state of understanding and forecasting. Obviously, such an ambitious approach will require strong leadership from local, state, and federal government officials with demonstrated track record of accurate, timely forecasts. Thus, as a community including both scientists and forecasters, these improvements must be put in place to steadily improve required predictability by the public over the next decade.

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Appendix A: The Tools

Several avenues of ongoing basic research utilize existing technological capabilities that could be improved in an integrated approach to examine the relevant science issues. In particular, a number of new instruments and platforms (Table A1) have become available in the last few years that can be utilized to vastly improve our understanding of the mechanisms responsible for TC track, intensity change, and improve the representation of surge, wind, rainfall, and severe weather in analyses and forecasts. In addition, there are a number of existing tools that can be utilized in new ways to improve our understanding.

A.1 Airborne-based or deployed observing systems

The NOAA G-IV is a state of the art, high altitude research platform. The G-IV has a certified ceiling of 12 km, a range of 7000 km, and a true air speed of 200 m s^{-1}. The aircraft is instrumented to provide 10-Hz flight level data, which includes high resolution GPS navigation information, radar altitude, pressure, all three wind components, temperature, and humidity. The primary instrument systems include a new GPS dropsonde system, a main aircraft data system and local area network capable of handling a number of specialized instrument systems, and a workstation for processing and encoding the data from the GPS dropsondes for direct transmission to the NOAA National Center for Environmental Prediction (NCEP) via a 2400 baud satellite communications link. This platform enhances TC forecast capability in three basic areas by providing: (1) large-scale environmental wind and height patterns to improve TC track forecasts; (2) a platform (complimentary to the NOAA WP-3D aircraft) for testing new instrumentation and flight plans as a means of developing the next generation TC reconnaissance capability; and (3) upper-tropospheric wind and thermodynamic data sets for research into TC intensity change and storm motion.

Expendables such as the GPS dropsondes, AXCPs, and drifting buoys, together with the NOAA G-IV and WP-3D, NASA and AFRES aircraft, provide the basis for an adaptable atmospheric and upper-oceanic sampling system that can provide detailed three dimensional observations of atmospheric wind, pressure, temperature, and humidity, along with upper ocean currents, temperature, and salinity within 1,000 km of TCs. The AXCPs have been shown to be effective in measuring the oceanic response in Hurricanes Norbert and Josephine (Sanford et al, 1987) and Gilbert (Shay et al, 1992). The expendables can be deployed over the data-sparse oceanic regions of the western Atlantic or Gulf of Mexico starting roughly 48-72 hours before the projected landfall of a TC on the coast of the United States. The GPS dropsondes define the TC's surrounding large-scale atmospheric flow, particularly in the middle troposphere—the layer most directly related to TC motion, whereas, the AXCP provide a spatial snapshot of the upper ocean's current and temperature structure, as well as, across the base of the OML to resolve the current shears associated with the upper-ocean cooling processes.

Drifting buoys developed by NOAA NDBC launched from AFRES aircraft into specific ocean areas ahead of TCs. As they drift in response to ocean currents and winds, they make measurements of the atmospheric pressure, air and sea temperature, wind speed, and wind direction. Two types of buoys can be deployed: Wind Speed and Direction (WSD) drifting buoys ; and Compact Meteorological and Oceanographic Drifter (CMOD) buoys. The WSD buoys measure surface wind speed and direction at a height of one meter, barometric pressure, air temperature, and sea surface temperature, while the expendable CMOD drifting buoys are capable of measuring air temperature, sea surface temperature, barometric pressure and position. The CMOD buoys are designed to store up to eight hours of data consisting of one ten-minute average per hour of all sensors, and the WSD buoys have been modified to provide continuous 10-minute averages of all sensors in addition to a three-hour history of the 10-minute average taken on the hour. Data from the buoys are relayed to ground stations via polar orbiting satellites. A buoy's position is determined each time a message is processed, thus allowing drift determination. Observations are processed and quality checks are performed at NDBC in a manner similar to that for moored buoys and other automated sites.

A suite of airborne remote-sensing instruments are available on the WP-3D aircraft for the purpose of measuring surface winds in and around TCs. A C-SCAT and a stepped frequency microwave radiometer (SFMR) have been flown together since 1992. C-SCAT conically scans the ocean surface obtaining backscatter measurements from 20° to 50° off nadir, and SFMR nadir brightness temperatures at six frequencies (4.6-7.2 GHz). The SFMR brightness measurements are used to estimate the emissivity of the ocean surface, derive estimates of the wind speed, wind stress, rain rate, and to calculate two-way attenuation suffered by C-SCAT due to precipitation. Applying this correction to C-SCAT's backscatter measurements, the normalized radar cross-section (NRCS) of the ocean surface are calculated.

The NASA/Goddard Space Flight Center (GSFC) has a long history of measuring the directional wave spectrum using the Surface Contour Radar (SCR) (e.g., Walsh et al, 1985). The Scanning Radar Altimeter (SRA), a mode of the 36 GHz GSFC Multimode Airborne Radar Altimeter, has replaced the SCR as the instrument of choice in the measurement of sea surface directional wave spectra. Both the SCR and SRA scan a narrow beam across the aircraft ground track, but the SRA has higher power and a wider swath. It measures the slant range to 64 points (versus 51 for the SCR) evenly spaced across the swath (at 8 m intervals for a 640 m altitude), converts them to surface elevations, and as the aircraft advances at a nominal speed of 100 m s^{-1}, displays the false-color coded topography on a monitor in real time. This grid of surface topography represents a snapshot of the wave field with along-track spacing of 12-13 m between points. These data over an along-track distance of 5-6 km and a cross-track swath of about 520 m are transformed into directional wave spectra by a two-dimensional fast-Fourier transform.

A.2 Ground-based observing systems

Upgraded surface observation capability, such as C-MAN and ASOS sites, in coastal regions likely to be affected by TCs to provide survivable high-resolution wind, temperature, and humidity records could provide details of the surface wind field as the TC makes landfall. These types of observations are critical to studies of storm damage, model and forecast verification, and information on the characteristics of the surface wind field as the storm moves inland.

NOAA has deployed a state of the art ground-based Doppler radar network over the entire U.S.. Nearly one-third of those radars are positioned along the portion of the coast threatened by TCs. The WSR-88D data is extremely useful for locating and tracking TCs. The radar data also provides high temporal (6 min) and spatial resolution (1° azimuthal X 1 km radial) wind fields useful in studies of the wind field characteristics. These data can also be used to construct 6-min resolution vertical profiles of the horizontal wind components over each radar site, providing details of the vertical structure of the wind as the storm moves over land.

Severe weather in TCs can compound an already difficult forecast problem. Damage from severe weather is not just confined to the region surrounding the eyewall, but often extends to the periphery of the storm. The WSR-88D severe weather observations seem to be useful in identifying some of these severe weather events associated with landfalling TCs such as tornadoes. However, these relatively small storms pose special obstacles for detection and warning for the new WSR-88D radars. Because the WSR-88D network is more widely spaced, no multi-Doppler analyses of these small TC-spawned severe storms have been accomplished. Mobile Doppler radar systems, such as the Doppler on Wheels (DOW) mobile X-band radars systems (Wurman et al, 1996), appear to offer the most hope of obtaining more detailed observations about the structure and dynamics of these unusual storms. Because static stability influences the turbulent wind field evolution, high-quality temperature and moisture data aloft from GPS dropsondes, rawinsondes and fixed and movable profilers equipped with a Radio Acoustic Sounding System (RASS) need to be employed.

Ocean surface current radars (OSCR) that utilize HF (25.4 MHz) and VHF (49.9 MHz) radio frequency can be deployed to map surface current patterns over a large area in the coastal ocean affected by TC landfall (e.g., Shay et al, 1995). The shore-based radar system consists of two units (Master and Slave) which are usually deployed 10 to 20 kilometers apart. Each unit makes independent measurements of current speed along radials emanating from its phased-array antenna system. The data are then combined to produce accurate vector currents (speed and direction) and display them in near-real time at 20 minute sample intervals. These measurements can be made simultaneously over areas as large as 700 km^2 resolving the tidal currents in potentially vulnerable coastal regimes.

Bursts in eyewall lightning activity appear to accompany storm intensification (e.g., Molinari et al, 1994). The NLDN may provide useful information to track TCs and monitor their intensity change. Given that the major portion of a TCs life is over open ocean outside the NLDN newer, long-range lightning networks being put in place now and satellite-borne lightning sensors, such as National Aeronautics and Space Agency's (NASA) Optical Transient Detector (OTD) and the planned Lightning Imaging Sensor (LIS) need to be examined (see satellite-borne observing systems for details). Techniques need to be explored to use these tools to track and monitor TCs.

A.3 Satellite-based observing systems

The entire U.S coastline affected by TCs is viewed via the GOES-8 (centered at 75°W) and 9 (centered at 135°W) satellites. The WV channel ~6.7 μm permits the user to keep track of water vapor at altitudes ranging from ~150 hPa (very moist conditions) to ~ 500 hPa (very dry) in the troposphere. Sequential water vapor images can be processed in an automated procedure to extract a WV-tracked wind vector (Veldon et al, 1997). The height of the wind vector is determined in part by utilizing the available atmospheric model analyses or short-term forecasts. Comparing the WV winds with radiosonde observations reveal the rms error is ~7 m s^{-1}. The magnitude of this error is a function of wind speed, with the smallest error at low winds and optimal performance occurring in a relative sense at high-wind speeds. These wind fields can be used to identify upper level meteorological features (e.g., troughs, ridges, jet streams) where a severe data void exists over the open oceans and at these altitude ranges. The ability to produce winds at levels ranging from ~ 150-500 hPa in cloudy and cloud-free regimes has been shown to be beneficial to the operational forecasters. Convergence and divergence in and around TCs is important in understanding the three-dimensional flow field, and when combined with lower-level winds from cloud-tracked winds and surface winds from either the SSM/I and/or the ERS-1 scatterometer. Three-dimensional wind information can then be used to determine vertical wind shear-a critical element in determining future TC intensities and track movement.

Radar altimetry from NASA's TOPEX/Poseidon Mission and the ERS-1 are needed to delineate the areal extent and time evolution of strong baroclinic features such as the Gulf Stream and warm core eddies. Of particular interest here is to infer variability in the OML depth to properly initialize the ocean and coupled atmosphere-ocean models using data assimilation methods. Adaptive sample strategies will be required to evaluate and validate the inferred OML depth variations in strong baroclinic current features for the purpose of estimated OML heat potential in the presence of advection.

The Optical Transient Detector (OTD) is the first space-based sensor capable of detecting and locating lightning events in the daytime as well as during the nighttime with high detection efficiency. The purpose of the sensor is to detect the full spectrum of lightning flashes, including cloud to ground, cloud to cloud, and intra-cloud lightning events. Ground-based techniques detect only cloud-to-ground lightning events which are believed to comprise 25% of the total lightning activity. In addition, these techniques generally detect lightning activity near land masses; very little information is provided regarding lightning events over the Earth's oceans. OTD is in a near polar orbit at an inclination of 70°, at an altitude of 740 km, providing continuous views of a 1300 km-wide region of the earth with 10 km spatial resolution and 2 ms temporal resolution.

A.4 Numerical Guidance

The operational GFDL, ETA and NOGAPS models and research models provide information about track, intensity, ABL structure and rainfall, yet only the track forecasts are undergoing evaluation and validation. These other important and available fields need to be assessed against the statistics of the observational data sets acquired using various observing tools. Comparison of research model (e.g., Regional Atmospheric Modeling System (RAMS), Mesoscale Modeling System (MM5), Advanced Regional Prediction System (ARPS)) landfall simulations to those of the operational models can be used to develop improved techniques for modeling track and intensity change. Objective analysis schemes, both operational and research, need to be improved and tested to assimilate data collected from the enhanced TC observing system.

A.5 Telecommunications

The World Wide Web (WWW) has opened up a new resource for researchers to share data sources. The TC research community could benefit from the development of some key data bases for testing hypotheses. We need to put all the available upsondes, dropsondes, flight-level data, ground-based and airborne Doppler products, WV winds, and GFDL, ETA, and NOGAPS model output on the WWW for use by the research community for track, intensity and other studies. Data storage and telecommunications strategies need to be developed to disseminate data resources to users.

Table A1. Tools readily available for addressing specific science issues relating to the forecast of track, intensity change and storm damage from landfalling TCs.

Tool	***Benefit***
Aircraft-based or deployed observing systems	
G-IV Aircraft	High altitude data and dropsondes
Expendables (GPS dropsondes, AXCP, drifting buoys)	Atmospheric and oceanic profiles
Airborne remote sensors (C-SCAT, SRA, SFMR)	Surface wind and current observations
Ground-based observing systems	
Upgrading surface observations (C-MAN, ASOS)	Improved surface observations
WSR-88D network	Wind profiles, Doppler winds, rainfall estimates
Portable remote sensors: OSCR, truck-mounted radars (DOW), and profilers (with RASS)	Surface wind and current observations. Wind and thermodynamic profiles and dual-Doppler winds
NLDN	Number of lightning flashes as an indicator of intensity change or severe weather
Satellite-based observing systems	
GOES WV and 1-min rapid-scan data	Irradiance fields, motion vectors
TOPEX and ERS-1 altimeter	OML heat potential
SSM/I	Surface winds and microphysics
ERS-1	Surface winds and waves
OTD	Number of lightning flashes as an indicator of intensity change
Numerical Guidance	
GFDL, ETA , and NOGAPS model output	Improved use of all simulated fields
Research Models (e.g., RAMS, MM5, ARPS)	Compare research model simulations to operational models
Operational and Research Objective Analysis Systems	Develop improved techniques to integrate mobile observations into models
Telecommunications (WWW)	
Data storage and telecommunications	Disseminate data and model output

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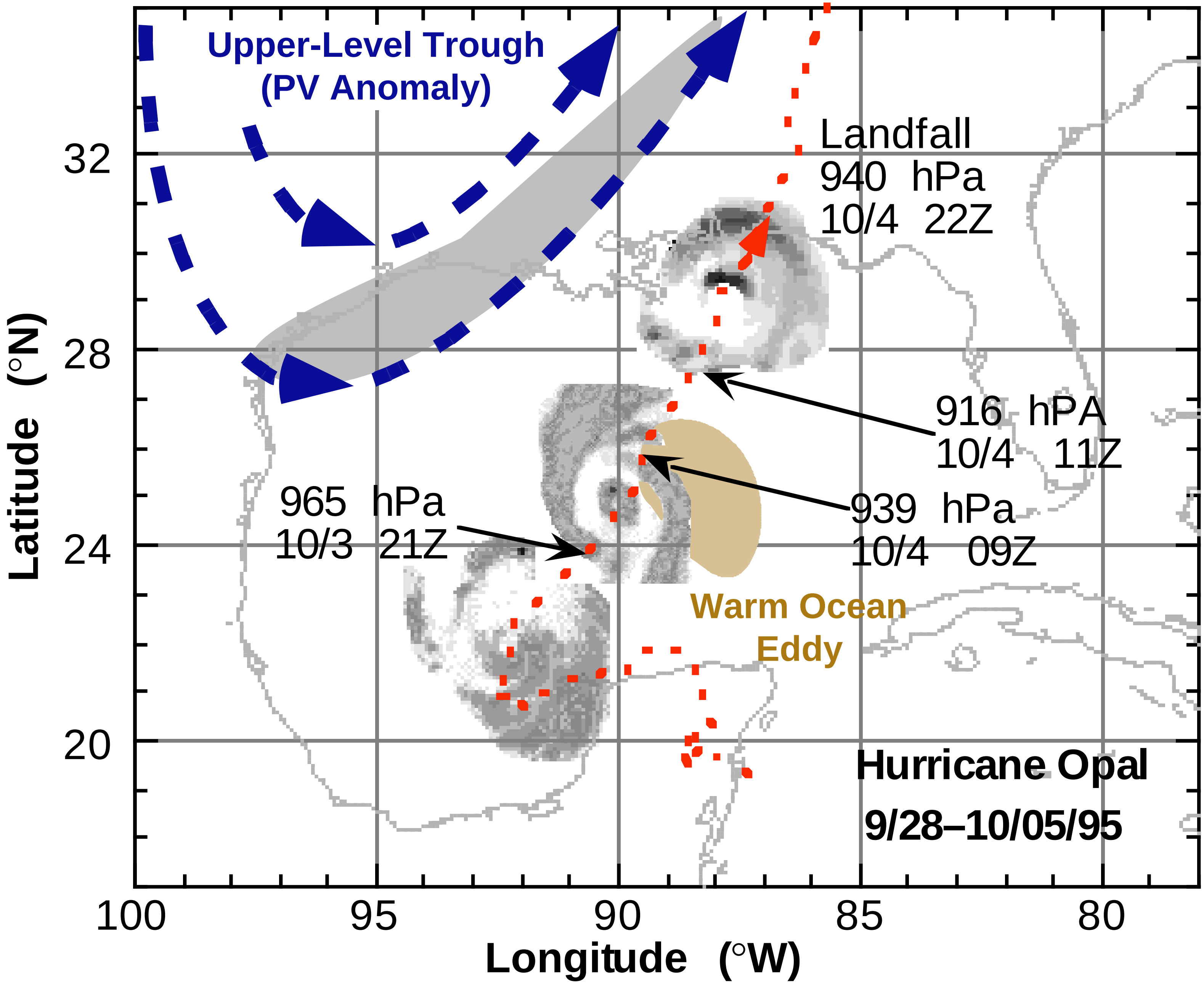
Figure Caption

Fig. 1. Track of Hurricane Opal from 28 September to 5 October 1995. The storm track is drawn as a bold dotted line. The upper level trough location at 1200 UTC, 4 October derived from upper-level analyses is denoted by the bold dashed line and the positive PV anomaly associated with the trough by the light stippling. The warm core ocean eddy location derived from TOPEX altimeter data is depicted by the dark stippling. The storms internal structure is represented by SSM/I 85-GHz imagery at 1629 UTC 3 October, 0337 UTC 4 October, and 1555 UTC 4 October. The 85-GHz black body temperatures are depicted as shades of gray, the darker shades denoting cooler temperatures, and therefore precipitation size particles. The SSM/I data was provided by Jeff Hawkins (Naval Research Laboratory/Monterey), and the TOPEX/Poseidon imagery used to find the location of the warm core eddy was provided by Gustavo Goni (Remote Sensing Group, University of Miami/Rosenstiel School for Marine and Atmospheric Sciences).



Upper-Level Trough
(PV Anomaly)
Landfall
940 hPa
10/4 22Z
916 hPA
10/4 11Z
939 hPa
10/4 09Z
965 hPa
10/3 21Z
Warm Ocean
Eddy
Hurricane Opal
9/28–10/05/95
32
28
24
20
Latitude (°N)
100
95
90
85
80
Longitude (°W)