8.1 RECENT RESULTS FROM NOAA'S HURRICANE INTENSITY FORECAST EXPERIMENT (IFEX)

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1. INTRODUCTION

In 2005 and 2006, NOAA's Hurricane Research Division (HRD), part of the Atlantic Oceanographic and Meteorological Laboratory, began a multi-year experiment called the Intensity Forecasting Experiment (IFEX). Developed in partnership with NOAA's National Centers for Environmental Prediction's (NCEP) Environmental Modeling Center (EMC) and National Hurricane Center (NHC), Aircraft Operations Center (AOC), and National Environmental Satellite Data Information Service (NESDIS), IFEX is intended to improve the prediction of hurricane intensity change by

- collecting observations that span the TC lifecycle in a variety of environments;
- developing and refining measurement technologies that provide improved real-time monitoring of tropical cyclone (TC) intensity, structure, and environment; and
- improving our understanding of the physical processes important in intensity change for a TC at all stages of its lifecycle.

Observations are collected in a variety of TCs at different stages in their lifecycle, from formation and early organization to peak intensity and subsequent landfall, decay over open water, or extratropical transition.

This paper presents a summary of the accomplishments of IFEX during the 2005 and 2006 hurricane seasons. Advancements were made in developing and refining measurement technologies to improve the estimation of TC intensity and structure, and a variety of field experiments were flown that spanned the lifecycle of the TC. Partnerships with other experiments during 2005 and 2006 also expanded the spatial and temporal coverage of the data collected.

2. IFEX ACCOMPLISHMENTS

The 2005 and 2006 Atlantic hurricane seasons was historic in terms of the number and intensity of TCs in the Atlantic basin, and the number of IFEX missions was commensurate with the amount of activity during the season. There were 51 NOAA P-3 and 60 NOAA G-IV research and operationally-tasked missions flown in a total of 15 different TCs or incipient TCs, with 2860 dropsondes. In addition to the flights by the NOAA aircraft, many of these flights were augmented by aircraft from operational Air Force Reserve WC-130 reconnaissance flights and partnering experiments, namely, the high-altitude NASA ER-2 aircraft during the NASA Tropical Cloud Systems and Processes (TCSP) project in July 2005, the NRL P-3 during the NSF-sponsored RAINEX project in August and September 2005, and the NASA DC-8 during the NASA African Monsoon Multidisciplinary Analyses (NAMMA) in September 2006.

The IFEX goals advanced during 2005 and 2006 hurricane seasons are briefly described below.

a) GOAL 1: Observations of TCs at various lifecycle stages

The distribution of flights stratified by TC lifecycle stage for 2005 and 2006 indicated roughly 20% of the flights were in TCs either in the depression or pre-depression stage, a much larger proportion compared with previous years. Many of these observations were collected as a part of the frequent-monitoring experiment:

1) Frequent-monitoring experiment

This experiment was designed to provide airborne Doppler data sets at all stages of a TC's lifecycle that can be used to improve the initiation and validation of the HWRF model. The flight module for this experiment was designed to be repeated every 12 hours (depression to weak hurricane stage) or 24 hours (mature hurricane stage), in either research or operationally-tasked missions to provide the maximum possible temporal resolution over the lifetime of the storm. With this flight strategy, five of the TCs had flights in them for most or all their lifecycle:

- Dennis (tropical storm to landfall)
- Gert (tropical disturbance to landfall)
- Katrina (tropical storm to landfall)
- Ophelia (tropical depression to extra-tropical transition)
- Rita (tropical storm to hours before landfall)

Airborne Doppler data collected during these flights was provided to EMC and is being used to develop advanced data assimilation and model validation schemes for HWRF.

b) GOAL 2: Development and refinement of measurement technologies

There were several new and refined measurement technologies made available this year to NHC. They provided valuable information to NHC that aided in the real-time assessment of TC intensity and structure.

1) Real-time Doppler radar analysis

Observations of the three-dimensional wind field of TCs provide significant insights into TC structure and dynamics. The first airborne Doppler observations of TCs were made in Hurricane Debby of 1982 (see review by Marks 2004). However, these early airborne Doppler

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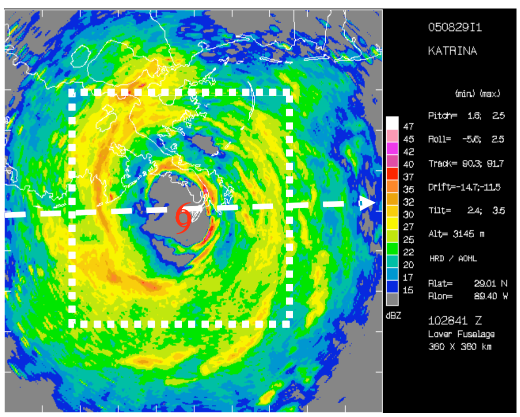
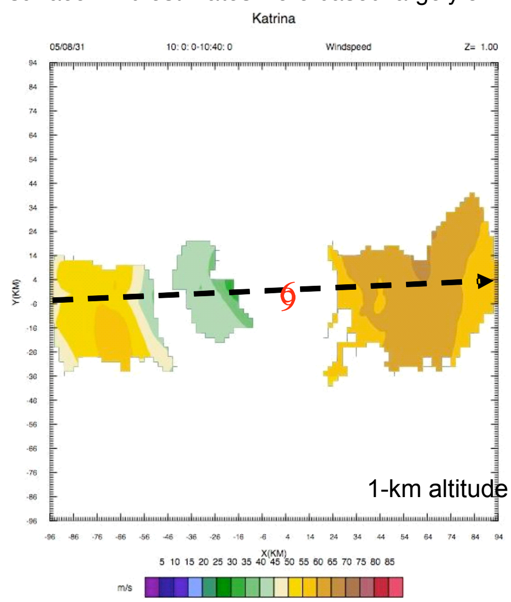
analyses of the three-dimensional structure of the winds in the hurricane core were time consuming. The quality of the data analyzed in these methods was controlled manually. For each passage of the aircraft through the TC center, quality control (QC) required more than a week.

During 2004 and 2005, HRD began development of a real-time analysis system that automatically performs QC, interpolates the Doppler data to a grid, synthesizes a wind field, and saves the QC data so they can be transmitted to EMC and assimilated into the HWRF model. Combined with the development of high-speed satellite communication that enables the transmission of large volumes of data from the aircraft in real time, these analyses have provided valuable information to NHC on TC intensity and structure. An example of each type of analysis is shown for the same passage of a NOAA P-3 through Hurricane Katrina on 29 August (Fig. 1). As can be seen from Fig. 1, important details about the structure of the wind field, e.g., the asymmetry in wind speeds at 1-km altitude and the deeper layer of strong winds on the east side vs. the west side of the storm, can be obtained from these analyses. This information proved invaluable to the forecasters at NHC for short-term forecasts of surface winds in a landfalling situation, and helped in determining the final intensity and structure of storms like Katrina.

2) SFMR algorithm refinement

Estimating hurricane surface wind maxima and distributions is a top priority of NHC. Until recently, surface wind estimates were based largely on





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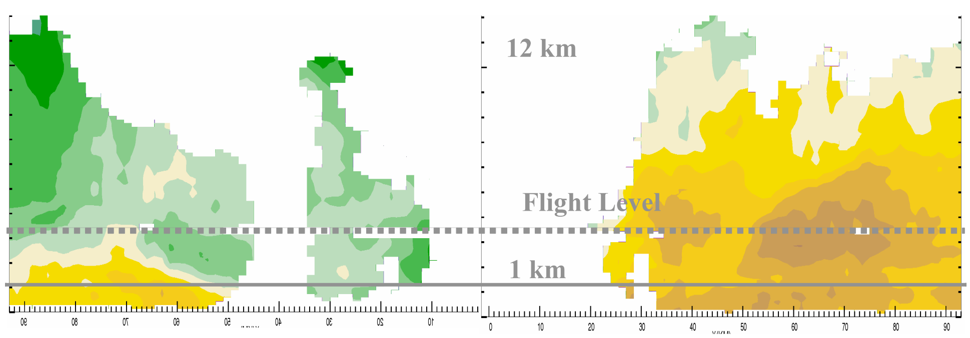

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Figure 1. (a) Lower fuselage radar-reflectivity (shaded, dBZ) of Hurricane Katrina in plan view at 1021 UTC 29 August 2005. Dashed box in (a) denotes analysis domain; (b) Horizontal analysis of total wind speed at 1-km level (shaded, m s^{-1}) obtained from airborne Doppler during a pass through Hurricane Katrina centered at 1020 UTC on 29 August; (c) Vertical cross-section analysis of total wind speed (shaded, m s^{-1}) taken from same pass. Dashed lines in (a), (b) and (c) show the flight track of the aircraft.

extrapolated reconnaissance aircraft flight-level wind observations and GPS dropsonde measurements of surface winds. However, there are drawbacks to these methods: extrapolating flight-level data involves considerable uncertainty, and dropsonde coverage is typically limited. For nearly 20 years, HRD has operated a SFMR on the NOAA P-3 research aircraft to estimate hurricane surface winds (Uhlhorn and Black 2003). The SFMR measures microwave brightness temperature at six different frequencies, and a retrieval algorithm uses a geophysical model to relate surface emissivity to wind speed and produce surface wind and rain rate estimates along the flight track (e.g., Fig. 2a). These measurements provide an independent estimate of surface winds with less uncertainty and better coverage than flight-level wind reductions or GPS dropsondes. Consequently, they are an important data source for NHC to diagnose the surface wind maxima and distribution. Beginning in 2004, a SFMR flew on one of NOAA P-3s for operational surface wind measurements, and in 2005 SFMRs were installed on both P-3s.

In particular, measurements were obtained from flights into Category-5 Hurricanes Katrina and Rita. These concurrent measurements, coupled with improvements to the GPS dropsondes enhanced their reliability in high wind speeds, enabling validation of the SFMR for surface wind speeds > 50 m s^{-1} (Fig. 2b).

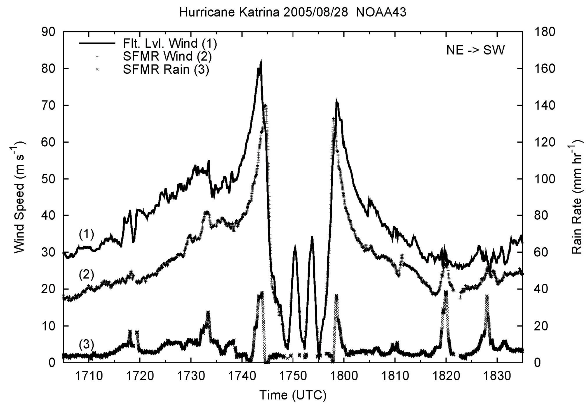
3) <u>Dropsonde improvements</u>

One of the primary instruments used on all aircraft involved in IFEX and NHC-tasked missions are the GPS dropsondes (Hock and Franklin 1999). A record number of dropsondes were released from the three NOAA aircraft during the 2005 and 2006 seasons. About 1100 of the ~2800 sondes were dropped from the NOAA P-3s within 300 km of the center of circulation of the TCs sampled.

Since its inception in 1997, the GPS dropsonde were not able to consistently record measurements in surface winds > 50 m s^{-1}, with more than 50% of the sondes failing to report winds within the lowest few hundred meters above the sea surface (Franklin et al. 2003). NCAR developed a prototype sonde with a new GPS receiver that was successfully tested during the 2004 hurricane season. NOAA and RAINEX began using this version of the sonde for research and operational missions as they became available in August 2005. Several hundred of these new GPS sondes were released in the eyewalls of intense Hurricanes Katrina and Rita. Preliminary evaluation of the performance of the new sondes indicates that their success rate was outstanding, with more than 90% of them reporting winds at or near the standard 10-m height. The data collected from the sondes in these storms were not only valuable to forecasters in real time in assessing the surface wind field, but will help improve our understanding of surface and boundary-layer fluxes.

4) <u>Use of unmanned aerial vehicles</u>

On 16 September 2005, aircraft from the govern-



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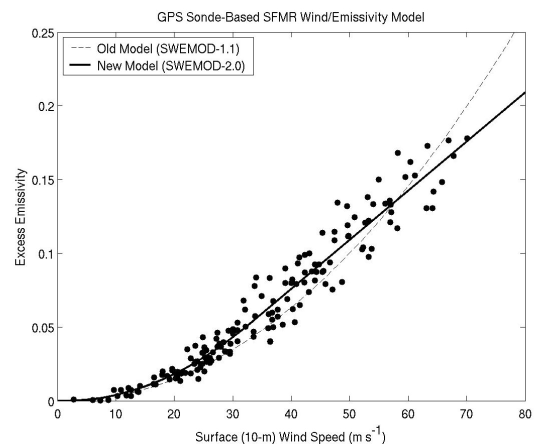

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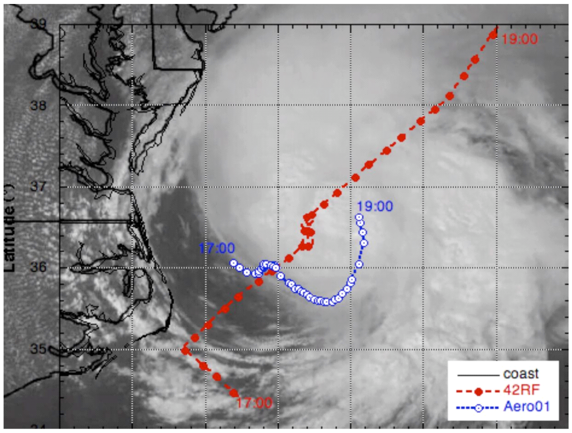
Figure 2. (a) Time series of flight-level wind speed (1, m s^{-1}), SFMR surface winds (2, m s^{-1}), and rain rate (3, mm hr^{-1}) from 1705-1835 UTC 28 August in Hurricane Katrina; (b) Scatter plot of emissivity measured by the SFMR compared with the wind speeds measured by dropsondes in the lowest 150-m layer for drops in Hurricanes Katrina and Rita. Two curves show old fit (old Surface Wind/Emissivity Model) and new fit (new Surface Wind/Emissivity Model)

ment and industry partnership of NOAA, NASA and Aerosonde successfully flew the first Aerosonde autonomous vehicle into Tropical Storm Ophelia. This landmark event occurred after Ophelia weakened to a 28 m s^{-1} tropical storm located off the North Carolina coastline (Fig. 3). The primary objective of this mission was to use the unique capabilities of the Aerosonde platform in order to document areas of the hurricane environment that are either impossible or impractical to routinely observe. The Aerosonde's closest approach to the wind center was 46 km southwest and 39 km northeast of Ophelia's center, coincident with a NOAA P-3 penetration of Ophelia's inner core. Peak Aerosonde winds at 750 m altitude were 33 m s^{-1} 75 km southeast of the center and 38 m s^{-1} 70 km north of the center, which were also the strongest winds observed in Ophelia on 16 September. SFMR winds southwest of the center were collected within 10 min of Aerosonde observations. Excellent agreement was found between



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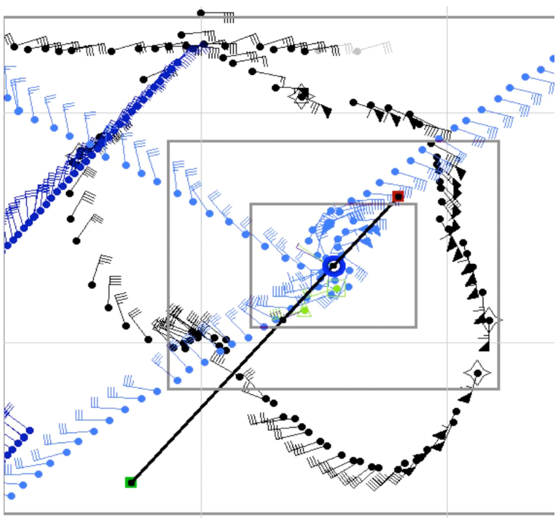

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Figure 3. (a) GOES-12 visible satellite image valid at 19 UTC 16 September 2005 for Tropical Storm Ophelia. Flight tracks of Aerosonde (blue) and N42RF P-3 (red) from 17 to 19 UTC overlain; (b) Storm-relative winds (m s^{-1}; flag is 25 m s^{-1}, full barb is 5 m s^{-1}) from surface-adjusted Aerosonde winds (black), N42RF SFMR winds (light blue) and a moored buoy (dark blue) for 1500-2000 UTC time window.

buoy, SFMR, and Aerosonde winds adjusted to surface values (Fig. 3).

A major success of the Ophelia flight was its operational impact. The Aerosonde was able to provide near-surface wind speed measurements to NHC in real time. In addition, high-resolution thermodynamic and kinematic observations within Ophelia's low-level inner core were also collected. Detailed analyses of these unique data sets has the potential of improving the understanding of surface and boundary-layer fluxes in TCs. The Ophelia Aerosonde data set will also provide detailed comparisons between in-situ observations and airborne as well as satellite-derived estimates. Data collected in such a unique location can also be used to verify operational and research numerical simulations.

c) GOAL 3: Improved understanding of the physical processes important in TC intensity change

The experiments described here were all designed to improve our understanding of the processes that are important in governing TC intensity change at all stages of their lifecycle, from tropical cyclogenesis to a mature storm to landfall or extratropical transition.

1) <u>Tropical cyclogenesis experiment</u>

This experiment was designed to study how a tropical disturbance becomes a tropical depression with a closed surface circulation, with a focus particularly on dynamic and thermodynamic transformations in the low- and mid-troposphere and lateral interactions between the disturbance and its synoptic-scale environment. This experiment addressed IFEX goals by taking measurements at the beginning of the life cycle of a TC to be used for evaluation and validation of the HWRF model.

There were two cases in 2005 for which the tropical cyclogenesis experiment was flown: a tropical disturbance in the East Pacific which possibly became Tropical Storm Eugene, and Tropical Storm Gert, which was first sampled as a tropical wave east of the Yucatan peninsula and developed into a tropical depression in the Bay of Campeche, ultimately making landfall as a tropical storm in southern Mexico. Gert was monitored every 12 h by P-3's for its entire lifecycle, and two of the P-3 flights were flown in coordination with the NASA ER-2 aircraft as a part of the NASA TCSP project. The measurements for each case included flight-level, Doppler winds and reflectivity, dropsonde profiles of wind, temperature, and moisture, and microphysical probe measurements of precipitating and non-precipitating hydrometeors from the P-3's, and reflectivity, vertical motion, temperature, and moisture profiles from the ER-2. The flights were targeted to regions of maximum convective activity within an identifiable cyclonic circulation, whether at the surface or the midlevels. The measurements provided by these flights should help to elucidate the mechanisms underlying the convective and mesoscale interactions important in tropical cyclogenesis.

2) <u>Saharan Air Layer experiment (SALEX)</u>

The main goals of SALEX are to better understand and predict how the dry air, mid-level easterly jet, and suspended mineral dust from the Saharan Air Layer (SAL) affect Atlantic TC intensity change. To assess the impact of this data on the GFS initial/forecast humidity fields and its forecasts of TC track and intensity, moisture information from the GPS dropsondes launched during these missions will be assimilated into operational parallel runs of the NOAA Global Forecast System (GFS) model. SALEX used GPS dropsondes launched from the NOAA G-IV (flying at ~200 hPa/~12 km) to examine the thermodynamic and kinematic structure of the SAL (Fig. 4a). The GPS dropsonde locations were selected using real-time GOES SAL tracking imagery from UW-CIMSS (Dunion et al. 2004) and mosaics of SSM/I total precipitable water from the Naval Research Laboratory. Specific effort was made to gather atmospheric information within the SAL as well as regions of high moisture gradients across its boundaries. The 2005 and 2006 G-IV SALEX missions included nine flights on four separate disturbances, one Hurricane Helene (2006). The first disturbance had two missions that targeted a SAL outbreak that was interacting with Tropical Storm Irene in 2005 (Fig. 4b). The second consisted of two missions and targeted two tropical waves that were interacting with the SAL, one of which developed into Tropical Depression 19 (2005) a few days after the missions were completed. The third was in and around Tropical Storm Debbie (2006).

3) Oceanic interaction experiment

A particular area of research identified to improve TC intensity forecasts is development of a better understanding of the interaction between the atmosphere and ocean during passage of a TC. It is well known that TCs produce a cold wake due to entrainment mixing due to vertical shear across the base of the ocean mixed layer (OML). Under certain circumstances such as slow-moving storms or a shallow OML, this cooling can have a negative feedback to the storm's intensity as the upper ocean cools to temperatures of < 26°C and enthalpy fluxes decrease. More recent research has documented the possible impact of oceanic warm-core eddies where OML's are considerably deeper (e.g., Jacob and Shay 2003). For these warm eddies and their parent, the Loop Current, the upper ocean cooling during TC passage is considerably less due in part to the deeper, warmer layers. As a result, enhanced moist enthalpy fluxes are sustained for longer periods of time as the storms pass over these features. If atmospheric conditions are neutral to favorable, these deep warm pools can aid in the intensification of the TC.

One set of experiments was conducted after Hurricane Katrina's passage. The objective of the airborne experiment was to examine the response of the eddy to surface winds approaching 75 m s^{-1}, and relate the *in situ* data to the satellite-derived fields. In a warm eddy coordinate system, airborne profilers were deployed from the NOAA P-3 over the Loop Current and warm core eddy regime on 15 September (Fig. 5). Hurricane Rita subsequently formed and moved through the Florida Straits and into the Gulf of Mexico. While Rita's path did not exactly follow Katrina's in the south-central Gulf of Mexico, it moved over the Loop Current on 22-23 September. During NOAA IFEX flights in the storm, profilers were deployed to document the thermal structure. In addition to the profilers released by the NOAA aircraft, an array of drifting buoys was deployed by the Air Force in the expected path of Rita to measure both mixed-layer temperatures and currents. As in Katrina, the deep, warm layers of the loop current provided additional heat to the atmosphere as Rita, under favorable atmospheric conditions, quickly reached

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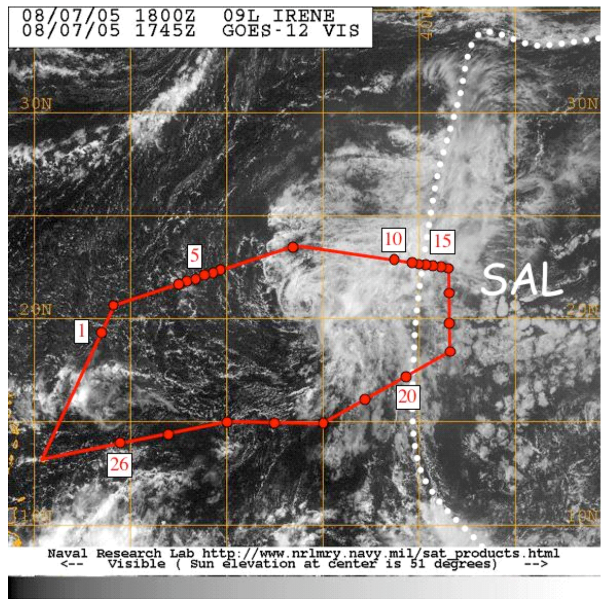

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Figure 4. (a) Photo taken from the NOAA G-IV on 27 September 2005 during a SALEX mission. At this time (~1820 UTC), the G-IV was cruising at 45,000 and was overflying a SAL outbreak in the central Atlantic. Vast amounts of suspended mineral dust (seen as a milky white haze) are evident in the photo. (b) GOES-12 visible satellite image valid 1745 UTC 7 August 2005 showing circulation of Tropical Storm Irene. Red line denotes track of G-IV for the SALEX mission (numbers represent GPS dropsonde locations); white dotted line denotes approximate boundary of SAL.

Category 5 intensity with surface winds of more than 75 m s^{-1}. The IFEX flight on 26 September deployed 53 temperature profilers at the same positions as the 15 September flight.

Preliminary analysis of the data revealed significant cooling of more than 5ºC as a cold core eddy observed south of the warm core eddy on 15 September advected cyclonically around it on 26 September between the Loop Current and warm core eddy. The observed

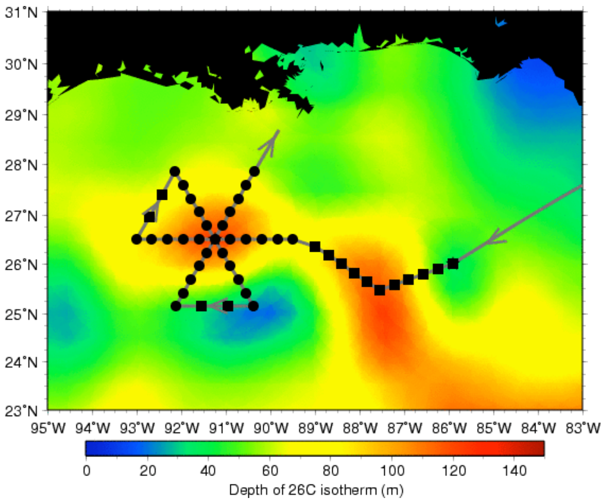

Figure 5: Post-Katrina (Pre-Rita) sampling pattern from the NOAA P-3 using a combination of Airborne Expendable Conductivity-Temperature-Depth (AXCTD, circles), Airborne Expendable Current Profiler (AXCP, circles), and Airborne Expendable Bathythermograph (AXBT, boxes) probes on 15 September relative to the depth of the 26°C isotherm based on an analysis of satellite altimeter measurements with a seasonal climatology. The same pattern was flown after Rita's passage on 26 September.

thermal structure revealed cooling of less than 1ºC in the surface mixed layer and a net oceanic heat content loss (relative to the 26°C isotherm depth) of about 10 kJ cm^{-2}, comparable to measurements from the passage of previous storms (Isidore and Lili in 2002). These data underscore the relative importance of the Loop Current and warm core eddies on hurricane intensity fluctuations that were first described during the Hurricane Opal case. Coupled models must accurately capture pre-storm variability to fully understand the oceanic response to atmospheric forcing as well as the atmospheric response to oceanic forcing. Such gridded oceanic data sets are important to evaluate the model initialization fields as well as the oceanic response from operational coupled models.

4) Landfall experiment

The TC life cycle ends either in landfall, decay over open water, or extratropical transition. This experiment was designed to study the kinematic TC structure just prior to and after landfall. During the 2005 Atlantic hurricane season, NOAA P-3 aircraft collected flight-level, SFMR, dropsonde, and airborne Doppler radar data in Hurricanes Dennis and Katrina while landfall teams from the University of Florida, Florida International University, University of Louisiana at Monroe, and Texas Tech University collected mobile surface wind tower data in these same systems.

The data collected during the landfall missions were used in real-time landfall and post-landfall wind analyses using H*WIND (Powell et al 1998). In the future, these datasets should help to address the IFEX goals of obtaining measurements at the end of the life cycle of a TC for use in the evaluation and validation of HWRF and collecting observations in a variety of atmospheric/oceanic conditions for use in assessing the influence of these factors on observed and model TC intensity and structure changes. Furthermore, the Dennis data set will be used to validate forecasts from an empirical inland wind decay model (DeMaria et al. 2006)

5) Extratropical transition experiment

During extratropical transition, the strength and distribution of surface winds, precipitation, and wave heights (if transition occurs over water) change rapidly, and warnings must be issued for impacts such as floods and high seas. Though the mean sea-level pressure generally rises and maximum surface wind speeds decay, the cyclone sometimes rapidly reintensifies into a significant extratropical storm. Since numerical models do not adequately simulate interaction between TCs and the midlatitude flow, the ability to forecast these major events is limited.

With the goal of understanding these interactions to improve forecasts, a collaboration with the Atmospheric Environment Service of Canada allowed for two NOAA P-3 flights into Hurricane Ophelia during its transition to an extratropical cyclone just before landfall in Nova Scotia. For the first time, the core dynamical structure was sampled by the P-3 airborne Doppler radar providing snapshots of the impact of dry continental air, decreasing sea surface temperature, and increasing static stability and vertical shear on the cyclone. Dropsondes released in the environment provided data on the downstream impacts of the cyclone, and also on the weak midlatitude cyclone to the northwest of Ophelia that allowed the storm to maintain its intensity across the Atlantic and into Arctic region north of Norway a week later.

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